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Proceedings of the Second Glacier Bay Science Symposium

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September 19-22, 1988
Glacier Bay Lodge, Alaska

Editors: A.M. Milner and J.D. Wood, Jr.

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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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Gustavus, Alaska

Sponsored by:
National Park Service
Friends of Glacier Bay
Glacier Bay Science Board

Edited by:
A. M. Milner
J. D. Wood, Jr.

U. S. Department of the Interior
National Park Service
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Anchorage, Alaska 99503

CONTENTS

page

Foreword vii

Acknowledgements viii

Opening Remarks — *Alexander M. Milner* ix

Welcome — *Marvin O. Jensen* xi

Keynote Address: Science at Glacier Bay: Weapon, Tool or Holy Writ?
— *Gregory P. Streveler* xiv

THE SESSIONS

SESSION 1 — PHYSICO-CHEMICAL PROCESSES

Plate-tectonic Setting of Glacier Bay National Park and Preserve and of Admiralty Island National Monument, Southeastern Alaska
— *David A. Brew* 1

Seismicity in the Glacier Bay Region of Southeast Alaska and Adjacent Areas of British Columbia
— *Robert Horner* 6

Gravity, Gravity-change and Other Geophysical Measurements in Glacier Bay National Park and Preserve
— *David F. Barnes* 12

Physical Factors Influencing Stream Development in Glacier Bay National Park, Alaska
— *Roy C. Sidle and Alexander M. Milner* 19

Groundwater Flow Systems and Geochemistry near the Margin of the Burroughs Glacier
— *William W. Simpkins and David M. Mickelson* 26

The Malaspina Glacier Radar Study: A SLAR Investigation of Glacial and Periglacial Features
— *John E. Jones, Bruce F. Molnia and James W. Schoonmaker, Jr.* 34

page

Channel-forming Processes Active in Queen Inlet, Glacier Bay, Alaska
— *Paul R. Carlson, Ross D. Powell, Douglas M. Rearic and Paula Quinterno* 41

Suspended Sediment Dynamics of Glacial Deltas: Implications for Maintenance of Submarine Channels
— *Andrew C. Phillips and Norman D. Smith* 47

Circulation and Suspended Sediment Dynamics in McBride Inlet, a Tidewater Glacier Fjord
— *Ellen A. Cowan and Ross D. Powell* 50

Iceberg-rafted Debris in McBride Inlet, Glacier Bay, Alaska
— *Paul F. Gottler and Ross D. Powell* 56

The Effects of Surging on a Proglacial Lake: Carroll Glacier, Wachusett Inlet
— *Norman D. Smith* 62

Advance of Glacial Tidewater Fronts in Glacier Bay, Alaska
— *Ross D. Powell* 67

SESSION 2 — RESEARCH RELATED TO RESOURCE MANAGEMENT AND HUMAN INFLUENCE

Movements and Habitat Use of Dungeness Crabs and the Glacier Bay Fishery
— *Charles E. O'Clair, Robert P. Stone and J. Lincoln Freese* 74

Commercial Fishing Patterns in Glacier Bay National Park, Alaska
— *Michael S. Taylor and Anjanette Perry* 78

Moose Colonization of Post-glacial Sites in Southeastern Alaska
— *Bruce Dinneford* 83

Ecology of Brown Bears on Admiralty Island, Alaska: An Overview of Ongoing Research
— *John W. Schoen* 86

Relationship between Prey Abundance and Usage of Glacier Bay by Humpback Whales
— *Kenneth J. Krieger* 90

page

Killer Whales in Glacier Bay and Icy Strait, Alaska
— *Dena R. Matkin* 96

Consistency and Change in Subsistence Use of Glacier Bay, Alaska
— *Robert G. Bosworth* 101

SESSION 3 — ECOSYSTEM DEVELOPMENT

Marine Intertidal Community Development following Glacial Recession in Glacier Bay, Alaska
— *Lewis Sharman* 108

Community Development in a Glacial Stream
— *Alexander M. Milner* 116

Benthic, Epibenthic and Planktonic Invertebrates in Ice-proximal Glacimarine Environs: Life in the Turbidity Lane
— *Charles A. Simenstad and Ross D. Powell* 120

Early Lake Ontogeny following Neoglacial Ice Recession at Glacier Bay, Alaska
— *Daniel R. Engstrom and Sherilyn C. Fritz* 127

Hydrologic Control of Lake Chemistry on Lester Island, Glacier Bay National Park
— *James E. Almendinger* 133

The Importance of Glacier Bay to Tests of Current Theories of Plant Succession
— *F. Stuart Chapin, III and Lawrence R. Walker* 136

Effect of Ecosystem Succession on Soil and Streamwater Chemistry in Glacier Bay
— *Robert Stottlemyer* 140

Inference and Verification in Chronosequence Studies at Glacier Bay
— *Christopher Fastie* 147

Dynamics of Old-growth Temperate Rainforests in Southeast Alaska
— *Paul Alaback* 150

page

SESSION 4 — SCIENCE AND MANAGEMENT

New Perspectives in Park Science
— *William E. Brown* 154

Managing a Biosphere Reserve: Incurred Responsibilities
— *Robert Stottlemyer* 156

How Should Ecologically Threatened Species Be Managed at Glacier Bay?
— *Gregory P. Streveler* 161

RECOMMENDATIONS

Physico-chemical Processes Panel 163

Panel on Research Related to Resource Management and Human Influence 163

Ecosystem Development Panel 163

Science and Management Panel 163

General Recommendations of the Science Panels 164

Recommendations of the Glacier Bay Science Board 165

FOREWORD

The Second Glacier Bay Science Symposium was held at the Glacier Bay Lodge in Glacier Bay National Park and Preserve, Alaska, on September 19-22, 1988. Jointly sponsored by the National Park Service, Friends of Glacier Bay, and the Glacier Bay Science Board, the principal objectives of the symposium were:

—— To provide bridges of communication between the various scientific disciplines;

—— To present the results of scientific research conducted at Glacier Bay during the past five years;

—— To examine the relationship between science and management in Glacier Bay; and

—— To discuss the future direction and role of science in Glacier Bay.

There is no doubt it was a unique symposium. The presentations and discussions concerned a variety of different disciplines, with participants from a number of generations relating to one relatively small, specific area of our globe.

One hundred and fifteen attendees from federal and state government agencies, academia and independent research institutes registered for the meeting. Thirty-six papers were presented during four sessions. A concurrent poster session and an evening scientific ethics panel discussion were also held.

On September 20th, the registrants boarded the MV *Spirit of Adventure* for a day-long trip to the Margerie and Grand Pacific Glaciers in Tarr Inlet and to Queen Inlet. Many interesting commentaries were made en route as the scientists recounted their research experiences and pointed out views of interest.

On the evening of September 21, the attendees met for a jolly gathering of swapping stories and showing slides that recounted some of their memories of Glacier Bay. This included a description of the canoe project by Richard Dalton.

The majority of the attendees felt the symposium was a tremendous success. However, the symposium, no matter how successful at the time, has not fulfilled its purpose until the proceedings are published as a record of the papers presented during those four days. These *Proceedings* are that record. The presentations are expanded here into short papers of approximately 3,000 words in length. Five of the verbal presentations were not submitted as short papers, and therefore their contributions will have to be recorded as program abstracts only. The recommendations from the panel discussions that followed each of the four sessions have been transcribed from the tapes of the meeting. The Program Chairman's opening remarks, Superintendent Jensen's welcome address, the keynote address by Greg Streveler, and the recommendations of the Glacier Bay Science Board are also included.

Alexander M. Milner
James D. Wood, Jr.
Editors

ACKNOWLEDGEMENTS

This symposium would not have been possible without the voluntary contributions of many people. The Symposium Steering Committee, composed of Gary Vequist, National Park Service; Larry Bright, Friends of Glacier Bay; and Alexander Milner, Glacier Bay Science Board, was responsible for the overall organization of the symposium. Additional assistance was provided by Carolyn Elder, Lynn Jensen, Lewis Sharman and Mike Tollefson.

The Steering Committee would like to sincerely thank the following people and organizations for their contributions: the Alaska Conservation Foundation; Glacier Bay Lodge, Inc.; John Scheerens and the staff of Glacier Bay Lodge; Boyd Evison, Al Lovaas and Marvin Jensen of the National Park Service; Dr. Donald B. Lawrence, Professor Emeritus, Department of Botany, University of Minnesota; Dr. William O. Field, retired glaciologist, American Geographical Society; and the noted author, Richard Nelson, for his comments and readings at the start of the Symposium.

The Steering Committee also expresses its appreciation to Jayne Johnson for typing the program; Maureen Milner for designing the poster and *Proceedings* cover; Mark Schroeder for transcribing the tapes; and the members of the Friends of Glacier Bay and the Glacier Bay Science Board. All contributed greatly to the success of the Symposium.

OPENING REMARKS

Alexander M. Milner
Program Chairman

On behalf of the Symposium Steering Committee, composed of Gary Vequist, National Park Service; Larry Bright, Friends of Glacier Bay; and myself, Sandy Milner, of the Glacier Bay Science Board, I would like to welcome everybody here. This fulfills one of the mandates of the last symposium, to hold another one in five years time--in September of 1988--and everyone looks exactly the same; nobody looks any older! It's great to see so many people here--researchers and people associated with the park for a long time, over many decades, and those that have just started to work in the bay. And also welcome to some new recruits to this world, perhaps only a few months old, who potentially may be researchers in future generations. They are being exposed early to the wonders of Glacier Bay.

I came over on the *Nunatak* on Tuesday. We were delayed by a day. I must admit that I was pretty frustrated. I had not been here for two years, and I had a particular desire to get back up the bay and look at the streams to see if there were any new insects in Nunatak Creek and if any fish were present. It had become an overwhelming desire to get up there, just as two years seems to be a long time to be away from this place. With the dramatic changes that have occurred here, two years can be like a hundred years somewhere else, or even two hundred years. Glacier Bay is such a dynamic place; its changes are so rapid.

And a dynamic place tends to attract dynamic people. This certainly appears to be the case here, with all the folks that have come to this symposium. In a number of ways I have been very fortunate to be Program Chairman, being able to interact with such dynamic people. But there were a few down moments. I had to write letters to Dan Mann, which is typically a low priority on my list. But I did it.

As I said, I have been very fortunate overall to be Program Chairman, because as the meeting approached you could feel the enthusiasm, the anticipation and the energy that was being generated toward the next three and one half days.

Of course, that's what's so unique about this symposium--the fact that we are talking about an area rather than a topic. I mean, I go to fish meetings every year, year in and year out, and we talk about fish year in and year out. I like fish, but it's just pleasant to come to a meeting where so many different scientific disciplines are represented. . . just to sit back and listen to talks concerning glaciers and terrestrial vegetation.

And I think this is another aspect that makes this symposium so unique. The interrelationships between the different disciplines and the fact that one of the main objectives is to foster the communication that bridges between the different disciplines, both through this meeting and through the different research activities planned for the next five years.

Another main objective of this symposium, of course, is to present the results of research conducted in Glacier Bay National Park and Preserve during the last five years. Other main objectives, perhaps just as important, are to examine the relationship between science and management in Glacier Bay and to discuss the future role and direction of science in the park.

There is one unfortunate absentee and, of course, that's Dr. William O. Field, who was very disappointed he was unable to come. He suffered a minor stroke three or four months ago. But he sends his best for the symposium, and he has sent us some material that is being displayed upstairs with the poster session.

The last symposium in 1983 was dedicated to William S. Cooper for his work in establishing the National Monument. We would like to dedicate this symposium to Dr. William O. Field, Dr. Donald B. Lawrence and Dr. Richard P. Goldthwait, who have an outstanding scientific record in the bay and have carried on that work for many decades.

I would now like to formally ask Superintendent Marvin Jensen to open the meeting.

WELCOME

Marvin O. Jensen
Superintendent
Glacier Bay National Park and Preserve

Good morning. It's my pleasure as Superintendent of Glacier Bay to welcome you to the Park and the Second Glacier Bay Science Symposium. The Science Symposium is sponsored by the National Park Service, the Friends of Glacier Bay and the Glacier Bay Science Board, and we owe them a debt of gratitude for their work in sponsoring this as planned from the last symposium that was held in 1983. Some people we should particularly thank for their individual efforts, at least that I'm aware of, are Sandy Milner of the Science Board, Carolyn Elder of the Friends of Glacier Bay and Gary Vequist of the Park Service, who made up the steering committee and who formed the heart and core of putting this meeting together.

Also, special thanks to Glacier Bay Lodge, Bob Giersdorf, Pete Donau, and especially John Scheerens and his staff for staying open a little bit later and providing the facilities we are in, particularly at a reduced rate.

Glacier Bay has a very strong scientific directive that extends from several primary things. One, of course, is the 1925 monument proclamation which says that it was established, among other things, for the unique opportunity for scientific study of glacial behaviors and of the resulting movements and developments of flora and fauna. And in 1980, the Alaska National Interest Lands Conservation Act strengthened that scientific directive by providing opportunities for scientific research on undisturbed ecosystems.

In addition, I think many of you know that in 1986 Glacier Bay was designated an International Biosphere Reserve, which also has a very strong scientific study mandate. In fact, that's one of the principal purposes of an International Biosphere Reserve.

When people think of a scientist, they often conjure up someone in a white lab coat working in some kind of sterile environment. But all of the scientists who study in Glacier Bay are far from that mental image, obviously. If a scientist had to choose a place to study, this is a most incredible place. As you heard Dr. Milner say, much of the reason for conducting research here is the place itself. It's like a home to the scientists who have worked here over the years. As I talked with a few of them I met last night, it is a place like home to them. So, in a sense, I welcome you all back home--and that comes from a "short-timer."

A lot of scientific research has been accomplished at Glacier Bay over the years. I think there will be, in the years to come, at gatherings like this, a lot more scientific research. As many of you know, and with what little bit I have learned, the bulk of the scientific research that was done in Glacier Bay was done by many of the people that are here with us this week at the symposium. Much credit we give to them for the work they have done.

For the National Park Service in Alaska and throughout the system, I see a change from what has been a visitor use-oriented approach to more of a resource protection and conservative mode. In Alaska,

I think we are on the vanguard of that approach. Our Regional Director is very strong in resource protection and protecting the values for which parks were established. He has developed a program of some magnitude, in terms of money and people, to address the need for knowledge for management. A lot of times we talk about managing resources and obviously we don't do that--the resources exist on their own. What we do is try to control the human uses in such a way that the natural systems can function on their own without being hampered. But we need a lot more information to minimize the human influences on the resources of the parks in Alaska.

Director Mott said, with respect to the program that was developed for Alaska, or proposed, I should say, here in Alaska, that we have the chance to do it right from scratch. But we must get plans to manage the parks based on solid research. The Regional Director, Boyd Evison, in characterizing his proposal for additional research and resource dollars, said that what we propose is going to be a road map and rationale for the most fundamental undertaking to be engaged in of any region in the National Park Service. It will put knowledge of park resources and their uses at the heart of all we do in this region. It will extend far beyond anything contemplated by the Service at this level. The effects will be profound and far-reaching on our ability to manage parks intelligently, on our perception of ourselves, on our priorities as an organization and on the way that others perceive us.

What he has proposed is an approximately eight million-dollar package of a combination of staffing, housing, labs, storage space and project money. That, obviously, would not come over one single year. In fact, it would probably take a good many years to accomplish throughout the parks in Alaska. At least it is a perspective of a need and one that has the support of the Alaska delegation. That may be a step in itself towards protecting the resources of the parks in Alaska.

I looked at the videotape of the last symposium. One of the things that it proposed as a goal for the park was to have a research scientist on the staff--I think by the time of the next symposium. Unfortunately, we don't have that. It's involved with and a part of the proposal of the Regional Director. It is, however, the number one priority for the region. The position has been approved and if the funding gets to be a little bit better than it looked at the first of the year, we may get a research scientist. What we are looking at--what is proposed--is a marine biologist. What I've looked at, at least over the last 50-60 years, has been terrestrial research. I looked at the marine system research that has been done and the objectives that have been written as a result of the 1985 review by the board. I think there were ten objectives, and of those ten, I think six have "no progress" on those particular objectives. I think that's indicative that there has probably been the least amount of research effort on the marine system of the park, and I believe that is one of our greatest challenges to manage. I think that is where most of the visitor use occurs; it's a place where we do have some amount of consumptive use, and it's a place where we have the least amount of information, and greatest need. I'm hopeful for this scientist/marine biologist position and I hope it will be funded this year, if not the following. Then we'll begin to take a more serious look at the needs of the marine system within the park.

It's obviously not a new discussion--as it's one that I saw on the videotape of the last symposium--but there is always a need to balance research with visitor use and protection of the park's resources. Balance it in terms of how much research is performed, where it might occur and the methods that might be used. I know this topic is scheduled for discussion during this symposium. I'm sure it will be a continuing dialogue for future symposia because we are always faced with the use/protect dichotomy that is inherent in the Park Service's Organic Act. It's an issue that has to be

continually balanced. As I mentioned, we have a strong mandate and it has to be balanced with the park's resources and the quality of the visitor experience. It is particularly fateful at this point in time because of the designation of wilderness values.

But now I'm just beginning to get into some of the meat of the symposium. It's great to have you all here. I look forward to getting acquainted with more of you, and I look forward to this week's proceedings.

Thank you.

KEYNOTE ADDRESS

SCIENCE AT GLACIER BAY: WEAPON, TOOL OR HOLY WRIT?

Gregory P. Streveler
Friends of Glacier Bay
Gustavus, Alaska

Early in this century, the Ecological Society of America almost singlehandedly convinced the U.S. government to remove a huge tract of land and water from most forms of settlement, subsistence use and commercial entry, and then install a management system giving science important status within it. This area was designated Glacier Bay National Monument. It later became a National Park.

During the six decades since this designation, science has exercised its prerogatives rather extensively at Glacier Bay, gaining access to one of North America's finest wildernesses and winning support from various public agencies for numerous investigations within it. Today we celebrate the results, as we did five years ago.

A part of me joins in the celebration. I have spent much of my life engaged in scientific thought, challenged and exhilarated by the power of that great tool for dispelling the mists of nature. It provides a delightful mental game, one that rivets my attention and satisfies a basic compulsion to investigate the world around me.

But a part of me does not feel like celebrating. One who is trained to feel the pulse of landscapes cannot help but sense a planet in deep, human-caused crisis and a park in which the tide of humanity is inexorably rising. I am aghast at our species' propensity for fouling its nest. I cannot help but wonder how many more science symposia can occur before a reckoning descends even on our fortunate corner of the world. This part of me sees our celebration as a form of fiddling while Rome burns, and I become impatient with our dalliance.

So before giving myself over to the celebration, I want to focus briefly on Rome and on the consequences of ignoring the flames. What should our role be in a world in deep crisis, and more particularly, if ironically, in a remote corner of the globe which has, so far, substantially escaped the crisis?

Before attempting an answer, I will first lay out an assumption you may wish to disagree with: there is no such thing as "theoretical" or "pure" research. All scientific endeavor is "applied." We are all applied to the earth. We, near the top of the pecking order of the world's dominant species, have many resources and much power at our command. Our decisions on how to use these in our professional as well as personal lives play a disproportionate role in the fate of the earth. Thus, none of us are sufficiently dissociated to be "theoretical." The result, I believe, is responsibility: we are morally compelled to make our work count.

Scientific work that is not designed to count in the world of today can be beautiful. So, I suppose, was Nero's music. But can it be taken seriously as a priority item in a hungry world? Can we in conscience ask that dwindling resources, notably including solitude, be expended on it? My personal feeling is

that unless we make our work count, it exists only for our own amusement and therefore has neither more nor less justification than, say, a trip to Muir Glacier to watch icefalls. Put baldly, we have no preferential rights in Glacier Bay unless we pull our weight.

Measuring science's track record in Glacier Bay is tricky business, but one yardstick could certainly be the degree to which knowledge accumulated here has been sown back into park management. To look into this, I selected fifty references specific to the park, more or less randomly from the card catalog of the park library, and reflected on the degree to which they have had an influence on park management, to the best of my knowledge (which now spans 22 years of active attention). I could find connection in only five cases.

This is not a perfect measure, as the lack of connection could be due to things other than the nature of the research or the deportment of the researcher. And of course, more than five could come to have a connection, say at some future time, if they provide a baseline against which to contrast an important change. But overall, the finding is not encouraging.

It would certainly be improper to end the analysis on that note. Our science must be judged in far larger arenas. And I am confident that at least some of what we have done here can stand on its merits in any form we choose. But too often, when asked to justify our privileged position in society and the world, we fall back on the old cliche that more knowledge is always good. This I reject. Knowledge has to be made useful. This means designing it to be useful, then placing it in the proper arena so that its utility can be exercised.

How can this be done at Glacier Bay?

First, we can make an effort to link our work to the real world. Most research topics can be made to bear practical fruit if sufficient thought is put toward that end during design and implementation. For instance, given present and likely future patterning of human use in the park, information from certain localities is far more useful to park managers than from others. The same is true for species, biotic communities and physical phenomena. Often these can be selected with little or no loss of theoretical acuity or professional gain, but it takes some understanding of management needs to select them properly.

We also need to make linkages between disciplines. Projects often proceed in a relative vacuum, even in some cases where the overt purpose of funding was to create a coordinated picture. Our present gathering can be a major vehicle for providing critical linkages, if we will use it as such.

Second, we need to communicate. Once we accept society's money and privilege to do science, we assume an obligation to take the results beyond a mental game we play with our peers. In the case of park research, we must present results in a digestible form and be available to explain them to park managers or interpreters as often as necessary in the face of changing needs and personnel. A publication on the shelf is a good beginning, but not necessarily an end.

Third, we need to clarify to ourselves and others the severe limitations on science as a tool of perception. On one hand, science dissects and simplifies nature in order to study it and thus is best at dealing with pieces. On another, science by itself lacks a moral dimension and thus is fundamentally blind as a societal tool. By obfuscating these points, by making science into a priesthood that encourages its ritual acceptance, we create a climate of unaccountability and so project a fuzzy image of science to the nonscientist. As a result, people often either reject out-of-hand this powerful tool, or expect far too much from it. Within the

National Park Service, even within myself, I have seen adherence to one extreme or another. The result is an erratic treatment of science in the park and a confused process of assimilating its results.

I believe that science will remain a loose cannon at Glacier Bay and elsewhere in our world until we learn to constrain it with other aspects of our humanity. Over the centuries since Francis Bacon, science has multiplied our society's power. To achieve this power, we have been complicit in a Faustian bargain, trading away brotherhood and sisterhood with the earth for dominion over it; empathy for objectivity; love for dispassion. And so the power thus won is self-absorbed, bereft of a moral rudder. Wielding it, we and our fellow citizens have become what Loren Eisley terms "world-eaters."

Ironically, it is becoming apparent that this bargain, in which we traded away much that is critical to our future, is unnecessary! The cutting edge of modern science itself has provided a view of the world that would astound Sir Francis. Ever greater precision and incision has not led to the description of the elegant cosmic machine he predicted. For the modern scientist, the universe is a surreal place where probability replaces certainty, matter evaporates into energy, location is without essential meaning, and form transmutes into process. Observer and observed are enmeshed into a single system. Unsettling terms have forced themselves into the most rigorous descriptions: terms like "duality," "paradox," "tendency to exist." In such a world, objectivity and dispassion are not only unnecessary, they may be theoretically impossible!

This view of reality does not require that the sacred groves be cut down. We need not drive the spirits away to achieve understanding. We need not call the brown bear a "resource" instead of a "brother."

The world-eaters have not yet consumed Glacier Bay. We may still have time to develop and exercise a revised science, one in which the great Baconian scalpel is guided by a hand sensitive to the world's pain and dysfunction; one that enfolds the earth instead of crushing it. Many of you, I know, hunger for this change as much as I. In fact, the beginnings are implicit in much current Glacier Bay research and in the substance of this symposium.

That is cause for celebration.

Plate-tectonic Setting of Glacier Bay National Park and Preserve and of Admiralty Island National Monument, Southeastern Alaska

by

David A. Brew

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Abstract

Glacier Bay National Park and Preserve and Admiralty Island National Monument together contain representatives of most of the tectonostratigraphic terranes and major geologic units of southeastern Alaska. These terranes and their bounding faults are from W to E: (1) the Pacific plate bounded on the east by the continental-margin or transitional fault; (2) the Yakutat terrane bounded by the Fairweather-Queen Charlotte Islands fault; (3) the Chugach terrane bounded by the Tarr Inlet suture zone, which itself has two bounding faults and contains both Wrangellia and Chugach-terrane rocks; and (4) the Alexander and Wrangellia terranes which are bounded by the Gravina overlap assemblage. Other tectonostratigraphic elements farther east are: the Coast Range megalineament; the boundary between the Alexander and Wrangellia terranes together and the Stikine terrane; the Stikine terrane; the Nahlin fault; and the Cache Creek terrane. The terranes originated far from their present locations and have been rafted about and juxtaposed by large-scale plate-tectonic movements. They have all moved relative to one another and have together moved northwards thousands of kilometers relative to North America. The westernmost terranes (Yakutat, Chugach, Alexander and Wrangellia) have been juxtaposed since about 120-100 million years ago when they first rafted in on the Farallon plate as it collided with the North American plate. More recent faulting and intrusive igneous events are also manifestations of large-scale plate movements and further complicate the interpretation of the plate-tectonic history. Removing relatively recent right-lateral separations of perhaps hundreds of kilometers on the transitional fault, of a few hundreds to several hundreds of kilometers on the Fairweather-Queen Charlotte Islands fault, of a few tens of kilometers on the Tarr Inlet suture zone, and of about 150 km on the Lynn Canal-Chatham Strait fault facilitates understanding of relations between these terranes. Such a reconstruction places the Yakutat terrane southward to about somewhere between the present latitude of Prince Rupert, B.C., and that of southern British Columbia; places the Chugach terrane southward to the same site plus an additional 100 km; places the Alexander terrane in the same general area; and, within the Alexander terrane, places the east end of Icy Strait southward to about opposite the south end of Admiralty Island.

KEY WORDS: Plate tectonics, tectonostratigraphic terranes, Admiralty Island, Glacier Bay, Alaska, faults.

In the 1970s the Canadian Cordillera in general, and the southeastern Alaskan part in particular, were the object of the earliest tectonostratigraphic terrane interpretations (Berg et al. 1972, 1978). These interpretations were that: (1) large (generally hundreds of kilometers long by tens of kilometers wide) blocks (or terranes) of the Cordillera between the North American craton and the Pacific plate are fault-bounded assemblages of rocks that had originated far from North America; (2) the terranes were accreted to the western margin of the continent by plate-tectonic processes; and (3) the terranes have contrasting preaccretionary stratigraphic, magmatic, metamorphic and deformational histories that cannot be explained by normal lateral variations within a single block. The rocks of Glacier Bay National Park and Preserve and of Admiralty Island National Monument (Fig. 1) were an essential part of these interpretations.

These early assertions were followed by more moderate interpretations that not all the terranes had moved great distances, but that all are "suspect" and should be considered "exotic" to North America until proven otherwise (Coney et al. 1980). Further interpretation has resulted in the disuse of some terranes, continued use of others, the division of others and the combination of still others into amalgamated "superterranes" (Monger et al. 1982; Monger and Berg 1987). No consensus exists for southeastern Alaska, but the original terrane interpretations have been greatly modified by Brew (1983), by Brew and Ford (1983) and in this paper.

Tectonostratigraphic Terranes and Major Faults

At present, eight major terranes are generally recognized in southeastern Alaska and adjacent regions (Fig. 2). The eight terranes are, from west to east: (1) the Pacific plate, (2) Yakutat terrane, (3) Chugach terrane, (4) Alexander terrane, (5) Wrangellia terrane underlain by the Alexander terrane, (6) Gravina overlap assemblage, (7) Stikine terrane, and (8) the Cache Creek terrane. Of these eight terranes, however, four (Yakutat and Chugach, Alexander and Wrangellia) are probably different-aged parts of two different terranes, and one (Gravina) is a locally derived overlap assemblage. Thus, there are only five terranes that are considered exotic to North America. All of the terranes except the Pacific plate, Stikine and Cache Creek are exposed in the Glacier Bay-Admiralty Island region.

Major active and inactive faults separate the terranes (Fig. 3): the Pacific plate is separated from the Yakutat block by the continental-margin or transitional fault (Davis and Plafker 1986) with perhaps hundreds of kilometers of right-lateral separation (right-lateral separation: the block on the right-hand side of the fault has moved toward the observer, however viewed); the Yakutat terrane is separated from the Chugach terrane (*sensu stricto*) by the Fairweather-Queen Charlotte Island fault, with about 550 km of right-lateral separation (Plafker et al. 1978; Plafker 1987); the Chugach terrane is separated from the Alexander terrane (and from the Alexander with overlying Wrangellia terrane) by the Tarr Inlet suture zone with probably a few tens of kilometers of right-lateral separation; the Alexander terrane is separated from the Gravina overlap assemblage by young high-angle faults and by an unconformity (Brew and Karl 1988); the Alexander terrane is separated from the Stikine terrane by the proto-Meade Glacier fault with an unknown amount of right-lateral separation; and (in British Columbia) the Stikine terrane is

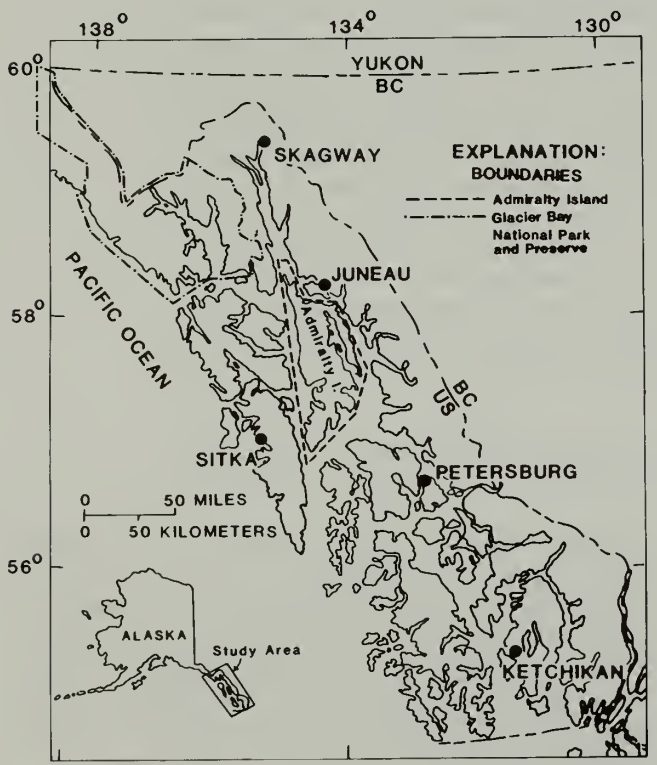
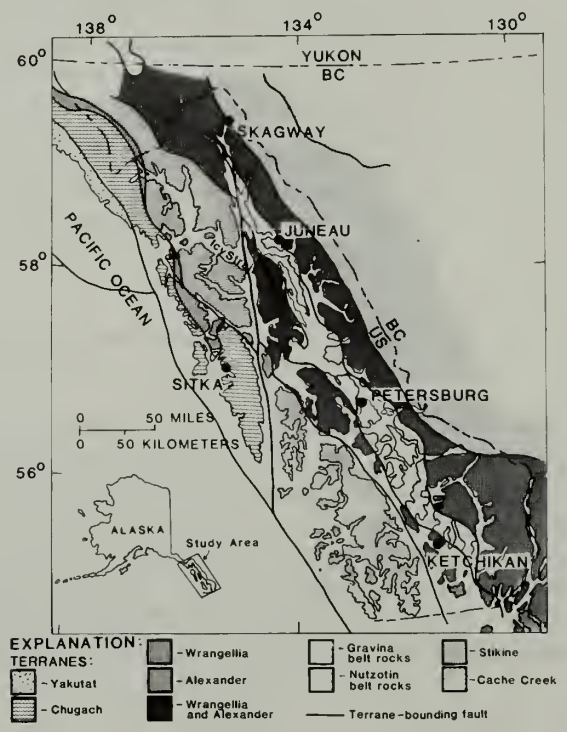


Fig. 1. Index map of southeastern Alaska, showing Glacier Bay National Park and Preserve and Admiralty Island areas.

Fig. 2. Tectonostratigraphic map of southeastern Alaska; radically revised from that of Berg et al. (1978).



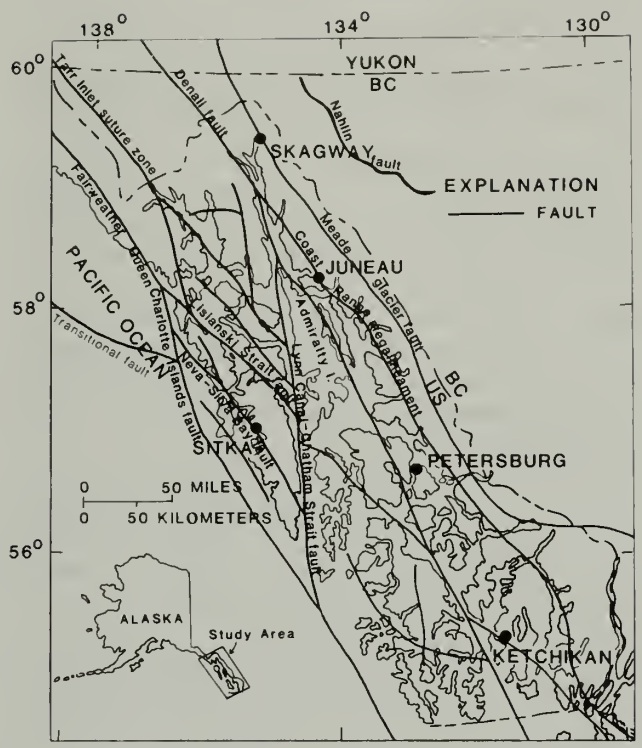


Fig. 3. Map showing major and minor faults of southeastern Alaska.

separated from the Cache Creek terrane by the Nahlin fault with an uncertain amount of right-lateral separation.

There are also several significant intraterrane faults within the Glacier Bay-Admiralty Island region: the Neva-Silver Bay and Lisianski Strait faults both have about 40 km of right-lateral separation, and the Lynn Canal-Chatham Strait fault (which is the southeastern continuation of the terrane-bounding Denali fault to the north and northwest but is here completely within the Alexander and Wrangellia terranes) has from 100 to 180 km of right-lateral separation (Ovenshine and Brew 1972; Sonnevil 1981; Hudson et al. 1982). The Coast Range megalineament is an important fault locally (Brew and Ford 1978).

In addition to the geologically determined relative separations, these terranes, except those of relatively local provenance, have northward displacement of thousands of kilometers based on interpretation of the paleobiostratigraphic and paleomagnetic evidence (Monger and Irving 1980; Newton 1983; Irving et al. 1985; Umhoefer 1987). Much of this major absolute displacement may have occurred on the Tintina fault-Rocky Mountain trench system, which lies in the Canadian Cordillera several hundred kilometers to the east of southeastern Alaska (Gabrielse 1985).

The terrane-bounding and other faults in southeastern Alaska define a mosaic of blocks that have undergone absolute vertical movements as well as the relative horizontal separations. The vertical movements as determined by different types of geologic evidence are shown in Fig. 4. The Saint Elias Mountain-Fairweather Range has undergone the greatest maximum elevation (perhaps 14 kilometers) since about 25 million years ago, and the western part of the Yakutat block has been depressed the most (perhaps 3 km) during the same interval (Davis and Plafker 1986). Blocks in the central part of southeastern Alaska, including Admiralty Island, have not changed significantly in elevation.

Among the faults and terrane boundaries, the Tarr Inlet suture zone is perhaps the most complex. The rocks in and adjacent to this zone record a complicated history of terrane origin, terrane juxtaposition, deformation, intrusion and faulting. Rocks of the Alexander terrane east of the zone are middle and late Paleozoic in age (about 420 to 245 million years old). Rocks of the Wrangellia terrane in the zone in the upper Glacier Bay area are interpreted to be early Mesozoic in age (about 230 to 210 million years old), whereas rocks of the Chugach terrane in the zone near Icy Strait are interpreted to be late Mesozoic in age (about 160 to 120

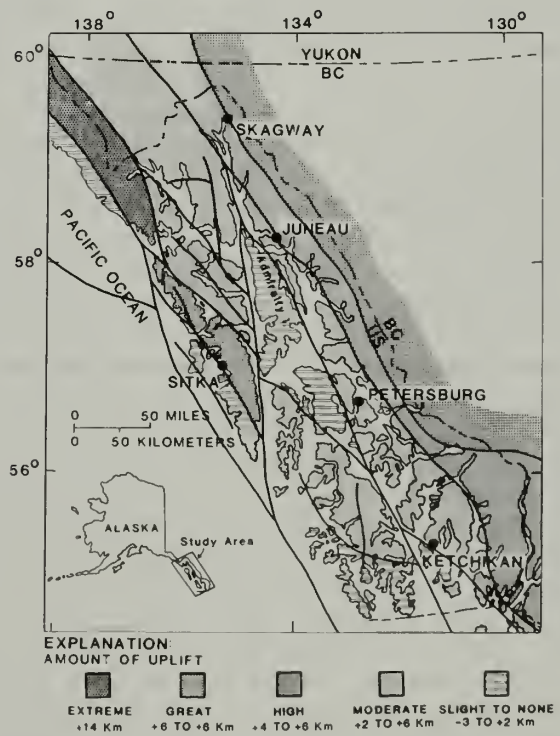


Fig. 4. Map showing generalized vertical movements of southeastern Alaska fault blocks. Displacements are relative either to depth of origin in the cases of metamorphic rocks and igneous rocks or to sea level in the case of volcanic rocks.

million years old), as are rocks of the Chugach terrane west of the zone. The rocks of the Wrangellia terrane in the upper Glacier Bay area were faulted against those of the Alexander terrane before about 110 million years ago, which is the age of granitic rocks that intrude both terranes there. The stratified rocks of the Chugach terrane west of the suture zone are interpreted to be about the same age as those intrusive rocks; those stratified rocks are interpreted to have been deposited in a distant place at the time the intrusions were being emplaced. These contrasting rocks of the same age were brought together by large-scale movement on the fault that forms the west side of the zone before about 28 million years ago, as shown by intrusions that cut across that fault. The 8-12 km elevation (Fig. 4.: 14 km minus 2-6 km) of the Fairweather Range has occurred since that time.

Plate-tectonic Movements

Several large-scale plate-tectonic interpretations are inherent in this reconstruction, which incorporates somewhat differing interpretations of these large-scale plate motions by different authors (Atwater 1970; Riddihough 1977; Engebretson et al. 1985; Debiche et al. 1987; Umhoefer 1987; and Pollitz 1988). Paleomagnetic and biostratigraphic evidence indicates that the Cache Creek terrane collided with North America at a much lower northern latitude in post-Late Triassic, pre-Middle Jurassic time. Stikine terrane collided with Cache Creek earlier in the same time interval at the same low northern latitude; and Alexander and Wrangellia terranes collided with Stikine terrane in early-Late Cretaceous time at the same latitude (Monger et al. 1982). The Chugach terrane has probably always been adjacent to the Alexander and Wrangellia terranes, but it collapsed against them in later-Late Cretaceous time and has also moved laterally (Berg et al. 1972; Plafker 1987). The Yakutat terrane is interpreted to be a displaced fragment of the Chugach terrane that has an additional overlying Cenozoic (about 65 million years old and younger) section of rocks. The Yakutat is interpreted to have been originally located a few hundred kilometers to the south and has been displaced to its present position during the last 20 million years (George Plafker, written commun. 1988); other geologists suggest that the Yakutat was displaced all the way from central California (Bruns 1977, 1983; Keller et al. 1984). The Pacific plate is actively moving northward alongside and under the Yakutat terrane (Davis and Plafker 1986). These collisions and northward movements of the terranes in southeastern Alaska and adjacent regions are major consequences of the generally eastward, northeastward, and northward movements of different oceanic plates in the Pacific basin and the resulting convergence with the north-northwestward-moving North American continental plate.

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Seismicity in the Glacier Bay Region of Southeast Alaska and Adjacent Areas of British Columbia

by

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Abstract

Three distinct zones of seismicity are observed in the Glacier Bay area. The most active zone follows the transform plate boundary along the coast of southeast Alaska. It has been ruptured by four major earthquakes this century with magnitude (M) $\geq$ 7. The very low level of seismicity presently observed suggests most accumulated strain is released in major earthquakes. The second zone, mainly in northern Glacier Bay, exhibits a NE-SW trend that may extend from the offshore Transition fault zone to the Denali fault zone north of Haines. The largest known earthquake in this zone, M 6.0, occurred near the British Columbia border east of Tarr Inlet in 1952. The third zone lies in the Coast Mountains east of Lynn Canal. Here the seismicity appears to be concentrated in distinct NE-SW elongated clusters. Seismicity and uplift inland from the plate margin may both be the result of convergence across the Fairweather fault. A recurrence relationship for this seismicity based on recent low-level data is given by $\log(N \geq M) = -0.72M + 2.84$. To assess the present seismic hazard and to understand the complex tectonic relationships will require: (1) improved seismic monitoring for accurate focal depth and mechanism determinations and (2) geodetic surveys to monitor ongoing crustal deformation.

KEY WORDS: Earthquakes, network capability, seismicity patterns, tectonics, recurrence rates, seismic hazards.

The first "precise scientific observation" of an earthquake in Alaska was made at Sitka on December 15, 1843 (Tarr and Martin 1912). Doubtless there were many other earthquakes before as there have been many others since. All parts of southeastern Alaska have been affected by earthquakes over the last century. The list of known events includes nine major earthquakes having magnitudes (M) of 7 or greater and begins with an unprecedented sequence in the Yakutat Bay area in 1899 (Fig. 1). The largest earthquake in Glacier Bay National Park and Preserve (GBNPP), M 7.9, occurred on July 10, 1958, near the southern end of the Fairweather fault. Casualties and damage were limited due to the sparse population. A M 6.0 earthquake that occurred just east of Tarr Inlet near the British Columbia border in 1952 (Horner 1983) provides evidence for significant seismicity inland of the plate boundary.

This paper examines seismicity patterns in the Glacier Bay region of southeastern Alaska and adjacent areas of British Columbia in relation to the major tectonic features. It follows an earlier study by Horner (1983) that first identified the significant zone of earthquakes in the northern part of GBNPP. Earthquake hazards are also discussed, and appropriate future studies are suggested.

The Historical Record — Network Capability

Only two permanent seismographs operated in Alaska before the destructive Prince William Sound earthquake in 1964. The first began operation at Sitka in 1904, the second at College in 1935. Only the larger earthquakes could be

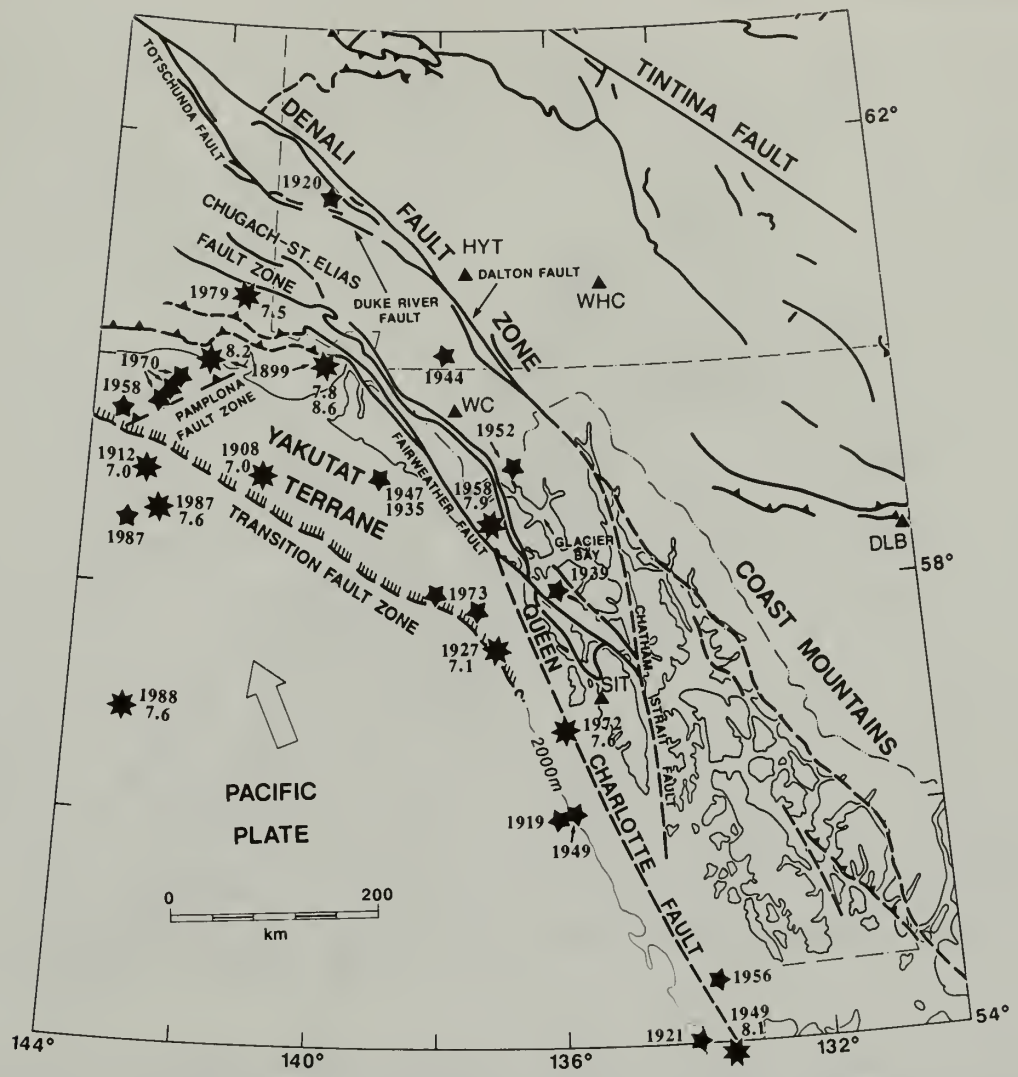

Fig. 1. Historical seismicity to 1988, M≥6, in southeastern Alaska and adjacent areas of British Columbia and the Yukon Territory superimposed on the major tectonic features (after Plafker et al. 1978). M 6 events are shown with only their year of occurrence. Arrow indicates relative motion between the Pacific and North American plates. Seismographs (triangles) currently operating in Canada, plus the station at Sitka (SIT), are also shown.

located by the worldwide seismograph network. Gutenberg and Richter (1954) give the following dates for completeness above certain magnitude levels: M≥7.75 from 1904; M≥7 from 1918; and M≥6 from the early 1930s. Significant location errors were common. The epicentres for the 1908 and 1912 earthquakes (Fig. 1), for example, were given to only the nearest degree of latitude. Larger earthquakes that occurred before the early 1900s, such as the 1899 sequence, were given epicentres near the points of maximum intensity. For lower magnitude events, the sparse population prevented accurate epicentre determinations.

Network detection and location capability improved greatly in the mid-1960s with the dramatic increase in the number of high-gain seismograph stations. All M 5 and larger earthquakes could now be located with an accuracy of about ± 25 km. Further improvement in detection to M 4 for the St. Elias region came with the installation of a seismograph at Whitehorse (WHC in Fig. 1) in 1971. The most significant improvement for the Glacier Bay region occurred with the installation of three additional seismographs in the southwest Yukon, west of Whitehorse, in 1978 (Horner 1983). This allowed location of all M 3 earthquakes with an accuracy of ±10-20 km. Since 1978, most earthquakes about M 2.5 and larger have been located. The seismograph stations currently operating in Canada are shown in Fig. 1. Not shown are the USGS seismograph stations in southeastern Alaska, located mainly west from the Yakutat Bay area. These stations have provided data for some of these earthquakes (see Stephens et al. 1980).

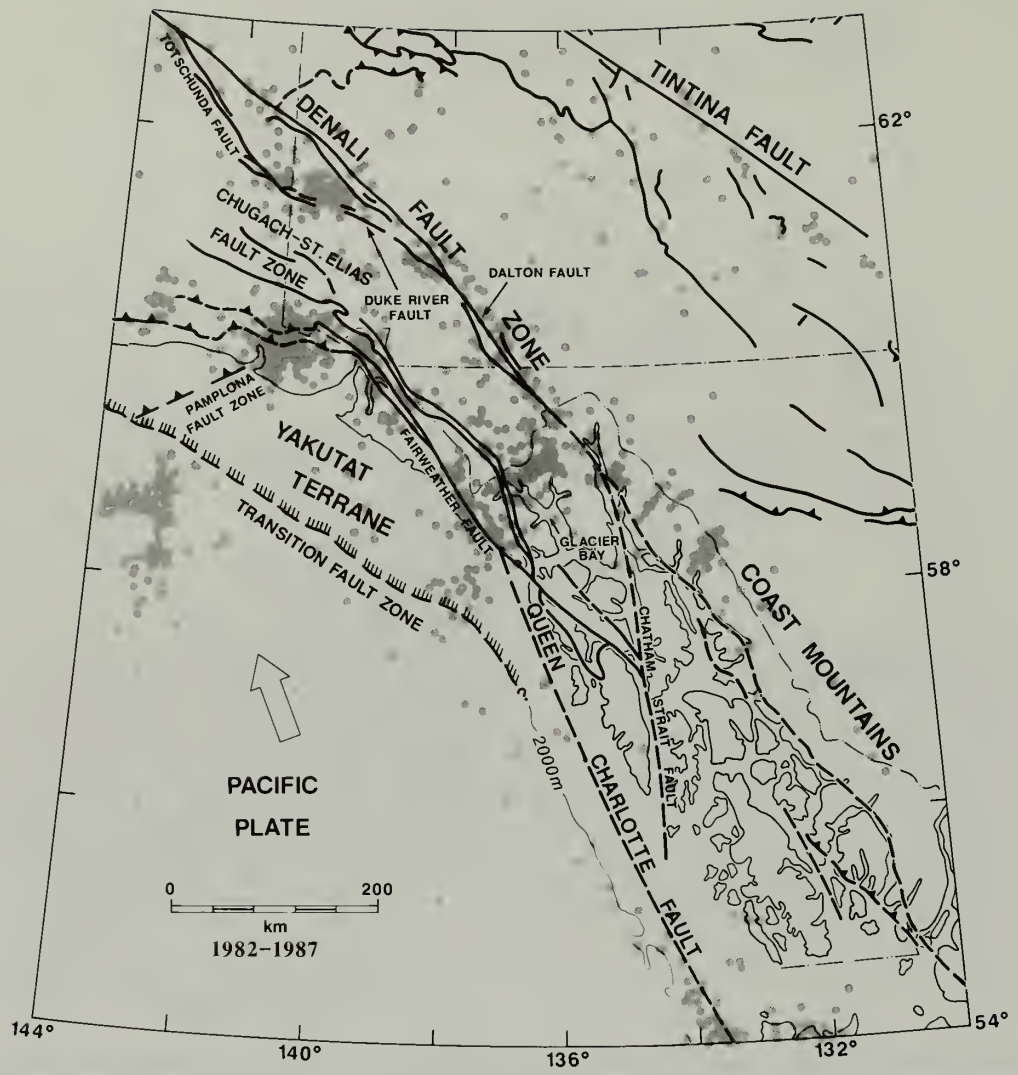

Fig. 2. Seismicity in southeastern Alaska and adjacent regions from 1982 to 1987, superimposed on the major tectonic features. Magnitude thresholds are about M 2.5 onshore and M 3.0 offshore.

Seismicity Patterns

In the eastern Gulf of Alaska, the Pacific plate moves about 6 cm/year in a NNW direction relative to the North American plate. Tectonic models for this region (Plafker et al. 1978; Perez and Jacob 1980; Plafker 1987) indicate most of the relative motion is accommodated by transform motion on the Queen Charlotte-Fairweather fault and convergence along the Chugach-St. Elias, Pamplona and Kayak Island fault zones to the west. The Yakutat terrane rides passively on the Pacific plate except for a small amount of convergence, about 1 cm/year, that is accommodated by motion along the shelf-edge Transition fault zone (Lahr and Plafker 1980). Most of the plate margin has been ruptured by major earthquakes over the last 90 years (Fig. 1). How the low-level seismicity patterns observed in southeastern Alaska, and GBNPP in particular, reflect this plate interaction and the current state of strain accumulation is an important question.

Earthquake epicentres in the St. Elias region from 1982 to 1987, determined by the Geological Survey of Canada, are shown in Fig. 2. Magnitude thresholds are about M 2.5 onshore and about M 3.0 offshore. Location errors are generally larger for the offshore events since they occur further from the seismograph network. The observed distribution of epicentres essentially maps the major fault zones in the area with some important exceptions. Intense activity is observed near the Fairweather fault, although it is not continuous. A 50-km segment across the Alsek River has had no earthquakes above our detection threshold over the last 10 years (Fig. 3). Similarly, very few earthquakes have occurred on the northern

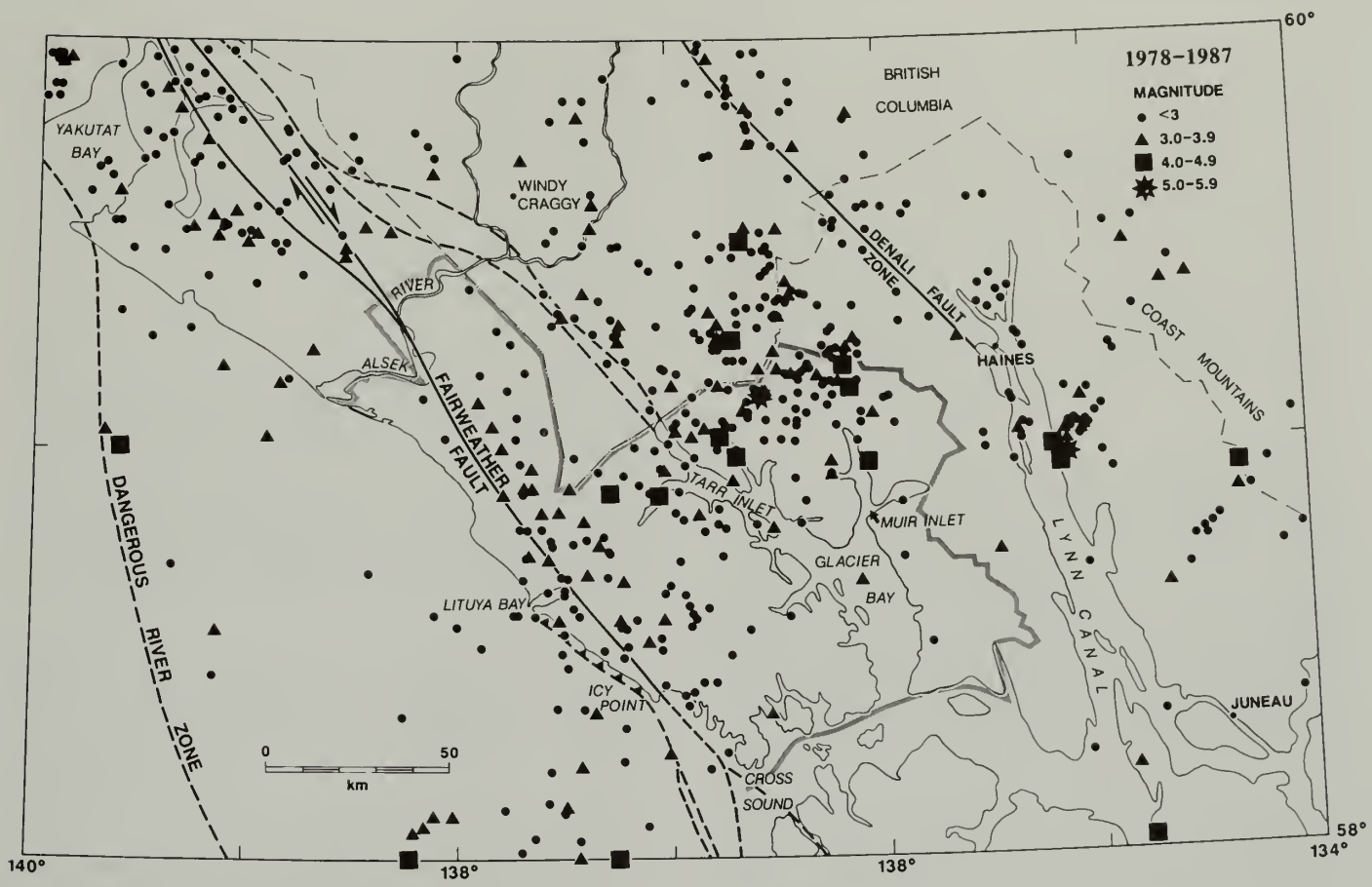

Fig. 3. Seismicity in the Glacier Bay region of southeastern Alaska and adjacent areas of British Columbia from 1978 to 1987. A temporary seismograph was installed at Windy Craggy, B.C., in June 1988.

segment of the Queen Charlotte fault immediately south of Cross Sound. Most of the events near this portion of the Queen Charlotte fault have, instead, occurred farther offshore. Mislocation errors cannot explain this offset. Significant seismicity in the Pacific plate is demonstrated by the two recent M 7.6 events (Fig. 1). The cluster in the Gulf of Alaska represents two aftershock sequences following M 6.9 and M 7.6 events in November 1987. There are also a number of events in the "continental" portion of the Yakutat terrane (Plafker 1987) east of the Dangerous River zone (Fig. 3).

Two significant trends that have emerged only because of improved low-level monitoring are seen in the Glacier Bay area and along the Coast Mountains. Fig. 3 is a more detailed map of this region showing seismicity observed over the last 10 years. The largest earthquake in this time period, M 5.9, occurred east of Tarr Inlet on September 15, 1985. The location is very close to the relocated epicentre of the M 6.0 1952 earthquake (Horner 1983). On September 14, 1987, a M 5.3 event occurred on the east side of Lynn Canal. It is the largest known in the Coast Mountains. An annual recurrence relationship for this seismicity is $\log(N \geq M) = -0.72M + 2.84$, where N is the number of earthquakes. The relationship is based on events from 1979 to 1986, located east of the Fairweather fault, between 58.0° N and 59.5° N. It suggests M 6 or larger earthquakes will occur about every 30 years.

Most of the earthquakes occur in the northern part of GBNPP in a cluster that straddles the Alaska-British Columbia border. To the west, the seismicity seems to merge with activity along the Fairweather fault. In fact, a strong northeast-southwest trend is evident that extends across the Fairweather fault, offshore to the Transition fault zone west of Cross Sound (Fig. 2). To the northeast, there may be a gap separating the seismicity on the Denali fault zone. In contrast, the seismicity to the east in the Coast Mountains is quite distinct. Very few earthquakes are observed south of Haines, between the east side of Glacier Bay and the west side of Lynn Canal (Fig. 3). In the Coast Mountains, the earthquakes appear to occur in northeast-southwest trending zones. The aftershock sequence of the M 5 earthquake on the east side of Lynn Canal exhibits the same trend.

Earthquake Hazards

Earthquakes pose an extreme hazard in southeastern Alaska. Coseismic deformation, strong ground shaking, rock and ice avalanches and other effects have already resulted in loss of life and property. The 1958 Fairweather earthquake (M 7.9) provides the best example to date. Maximum coseismic displacement was measured near Crillon Lake, where the southwest side of the fault moved about 6.5 m to the northwest and 1 m up relative to the northeast side (Tocher 1960). Fault displacement was observed from Palma Bay to Nunatak Fjord. The earthquake triggered a large rock avalanche with a volume of about 30 million m^3 at the head of Lituya Bay. The avalanche generated a water wave that surged down the bay denuding both shorelines to an elevation of about 60 m. Two fishing boats near the mouth of the bay 11 km away were sunk, which resulted in two deaths. On the shore opposite the rock avalanche the water wave reached an elevation of 530 m (Miller 1960). The strongest ground shaking occurred on the coastal lowland southeast of Yakutat, causing extensive fissuring and sandblows. Part of Khantaak Island, located just offshore near Yakutat, subsided about 30 m resulting in three more deaths (Davis and Sanders 1960). Other effects included the damming of the Alsek River because of accelerated ice calving from the Alsek Glacier. Flooding followed a few hours later after the ice dam gave way. Similar effects can be expected from future earthquakes, not only on the Fairweather fault or in GBNPP but also from more distant locations (see Stover et al. 1980).

The recurrence interval for M 7.9 or larger earthquakes on the plate boundary along the coast of southeastern Alaska, based on historical data, is about 120 years (Horner 1983). Earthquakes M 6 or greater would be expected about every 5 years. For the Fairweather fault alone, Lisowski et al. (1987) calculate a recurrence interval for a M 7.9 earthquake of 67 to 85 years from measured deformation rates and an average coseismic slip of 3.5 m. They also conclude that if one of the 1899 Yakutat Bay earthquakes also ruptured part of the Fairweather fault, then the recurrence interval could be as short as 60 years.

Discussion

One of the significant observations from improved monitoring over the last decade is the very low level of seismicity observed on the Queen Charlotte-Fairweather transform boundary, north of the Queen Charlotte Islands. No events larger than M 4 have occurred in this interval, and the segment south from Cross Sound can be considered almost aseismic. It would appear that virtually all the accumulated strain is released in major earthquakes. This is consistent with the very high strain rates measured in a narrow zone across the northern segment of the Fairweather fault (Lisowski et al. 1987). The rates are several times those measured on the San Andreas transform fault in California, for example. Lisowski et al. (1987) conclude the fault zone is locked to depths of 7 to 9 km. A similar conclusion is reached by Page and Lahr (1971) for the southern segment of the Fairweather fault.

The concentration of seismicity on the southern segment of the Fairweather fault could be considered somewhat anomalous and may be related more to the seismicity trend through Glacier Bay than to activity on the plate boundary. The Fairweather fault is oriented about 20^0 counterclockwise to the relative motion direction of the Pacific plate and results in 10 to 20 mm/year convergence across the Fairweather fault (Perez and Jacob 1980, Lisowski et al. 1987). It seems more than coincidence that this change of strike and the southern edge of the northeast-southwest Glacier Bay trend so closely coincide (Fig. 2).

Convergence across the Fairweather fault may be responsible for both the seismicity and high uplift rates observed in the Glacier Bay area (Horner 1983). Hudson et al. (1982) report regional uplift over an area at least 500 km long by 200 km wide. Although Hudson et al. (1980) attribute most of the rapid uplift to glacioisostatic adjustment, they also conclude, because of the regional extent of the uplift, that a tectonic origin is possible and the uplift could be related to strain buildup along the transform boundary. This may also explain the seismicity in the Coast Mountains since it would roughly coincide with the edge of this zone of deformation.

Two studies needed to better understand the complex seismotectonics in the Glacier Bay area are: (1) improved earthquake monitoring and (2) crustal deformation measurements. An improved seismograph network would provide more accurate epicentre locations and could be accomplished with one or two permanent seismographs in Glacier Bay. Focal mechanisms and focal depths (which cannot be determined in the Glacier Bay region now) could be obtained with detailed microearthquake surveys over relatively short periods of time. Precise geodetic surveys would provide accurate information on regional deformation and strain rates. A network of global positioning satellite (GPS) or geodynamic laser ranging satellite (GLRS) control points could monitor secular strain as well as resolve possible strain rate variations associated with large earthquakes. The network should extend from the west side of the Fairweather fault to the Coast Mountains and the north side of the Denali fault zone.

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Gravity, Gravity-change, and Other Geophysical Measurements in Glacier Bay National Park and Preserve

by

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Abstract

Tide-gauge records show that Glacier Bay is an area of rapid regional uplift, averaging nearly 4 cm/year during the past 40 years. This uplift was originally ascribed to isostatic rebound following retreat of the glacier ice, but geologic and geophysical evidence suggest that the Glacier Bay area is also affected by tectonic processes that may predominate over processes of isostatic adjustment.

Reconnaissance gravity coverage of Glacier Bay National Park is nearly complete and includes data acquired from both shoreline traverses and helicopter stations on land. Radar ice-thickness measurements were used to correct the gravity data where helicopter landings could only be made on the glaciers. The highest Bouguer anomalies are near the peaks of the Fairweather Range and are caused in part by the exposed gabbroic plutons. Conversion of these Bouguer anomalies to isostatic anomalies and comparison of those anomalies with the isostatic map of the conterminous United States shows that the Glacier Bay National Park and Preserve anomalies are the highest in the United States. This high isostatic gravity may in part be due to a broad regional free-air gravity high, which satellite data suggest extends over a large part of south-central Alaska and the northwest Pacific.

Measurement of the gravity change accompanying the uplift may provide an additional tool for studying the uplift mechanism. Although there is a greater than (?) 30-year record of gravity measurements in the park, a 1969 pair of measurements at Gustavus airport in 1989 is probably the first sufficiently precise baseline from which to record changes. As repeated measurements at this station have not yet detected a change, the uplift process probably involves elastic compression. However, a better network of high-precision gravity stations is needed. The accumulated geophysical data show that Glacier Bay National Park and Preserve presents a unique opportunity to study active geologic processes responsible for crustal uplift.

KEY WORDS: Gravity, gravity-change, uplift, tectonics, ice thickness, geophysics, tides, isostasy, sea level, Glacier Bay, Alaska.

Gravity studies in Glacier Bay National Park and Preserve were initiated during a statewide reconnaissance (Barnes 1977), were later extended as part of a mineral assessment (Barnes et al. 1978), and are now beginning to contribute to our understanding of the geologic processes responsible for the regional uplift of the area. This uplift is apparently the most rapid in the United States (Hicks et al. 1983); tide gauge records at Bartlett Cove indicate an emergence rate of about 4 cm/year (Hicks and Shofnos 1965). Isostatic rebound following retreat of the glacier ice was initially considered to be the cause of the uplift, but the gravity data near other examples of isostatic uplift do not resemble the data at Glacier Bay.

In Scandinavia the isostatic uplift is centered on a distinct gravity low near the Gulf of Bothnia (Niskanen 1939), and the isostatic gravity map of North America (Simpson et al. 1988) shows a good correlation between the distribution and thickness of the continental ice sheet in Pleistocene time and the location of a regional gravity low over arctic Canada. Low gravity associated with isostatic uplift following glacial retreat is considered evidence of crustal depression caused by the ice load (Garland 1965). In contrast, high gravity anomalies are the predominant features of the Glacier Bay map. Finally, the lack of a detectable gravity change associated with the rapid uplift at Glacier Bay is evidence that tectonic compression is more significant than isostatic rebound.

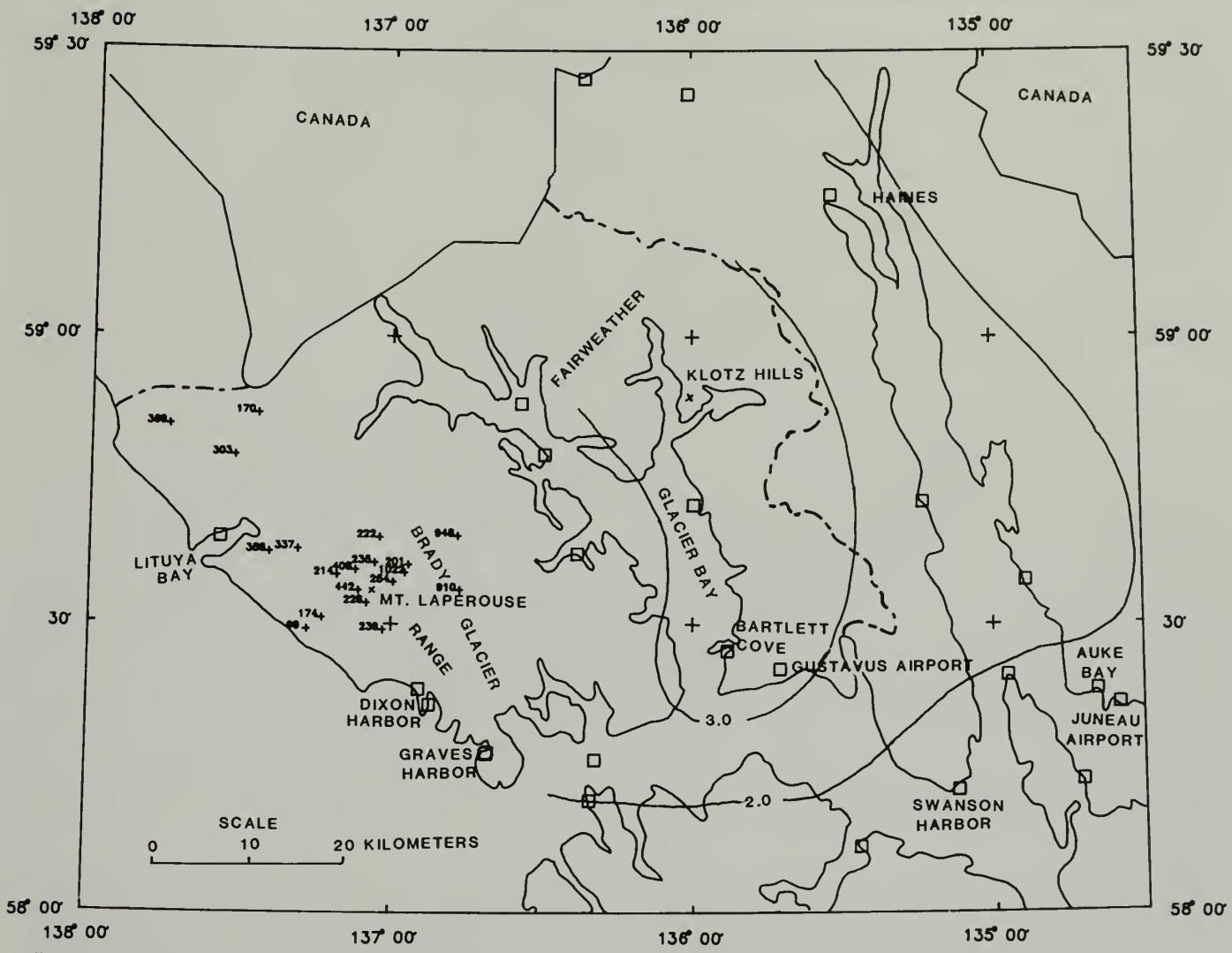

Fig. 1. Map of crustal uplift contours, glacier ice thicknesses, and multiple-occupied gravity bases of the U.S. Geological Survey in the area of Glacier Bay, Alaska. Crosses with numbers indicate locations of selected radar measurements and glacier-ice thickness in meters. Squares are gravity base stations used in the 1972 and 1976 shoreline surveys. Place names are those mentioned in text. Uplift contours are adapted from Hicks and Shofnos (1965) and indicate uplift rates in cm/year. Dot-and-dash line is boundary of Glacier Bay National Park and Preserve.

Regional Uplift

Regional uplift extends over most of the northern half of southeastern Alaska and was first detected at Sitka and Juneau, where tide recorders have operated almost continuously for more than 50 years. In 1959 and 1960, the U.S. Coast and Geodetic Survey reoccupied many stations where tides had been previously recorded for periods of a few days to a few months (Pierce 1961). These 1959 and 1960 data showed that the most rapid uplift of nearly 4 cm/year was located at Bartlett Cove. Hudson et al. (1982) reoccupied many of these tide-gauge stations for shorter observation periods in 1979 and showed that the regional uplift is continuing and that the area of most rapid emergence may have moved northward to the upper part of Glacier Bay. The westward and northward extent of the uplift is poorly known because comparative data have not yet been published for tide-gauge locations along the park's outer coastline.

Other types of studies have also been used to determine the location and amount of uplift. Geomorphic studies using the dates and elevations of raised beaches also show the regional uplift (Derksen 1976), and such studies suggest a maximum rate of uplift in recent centuries as high as 4.5 cm/year near the Klotz Hills in the north-central part of the Bay (Goldthwait 1987). On a much longer time scale, Brew's geologic studies (this volume) suggest that rocks of the

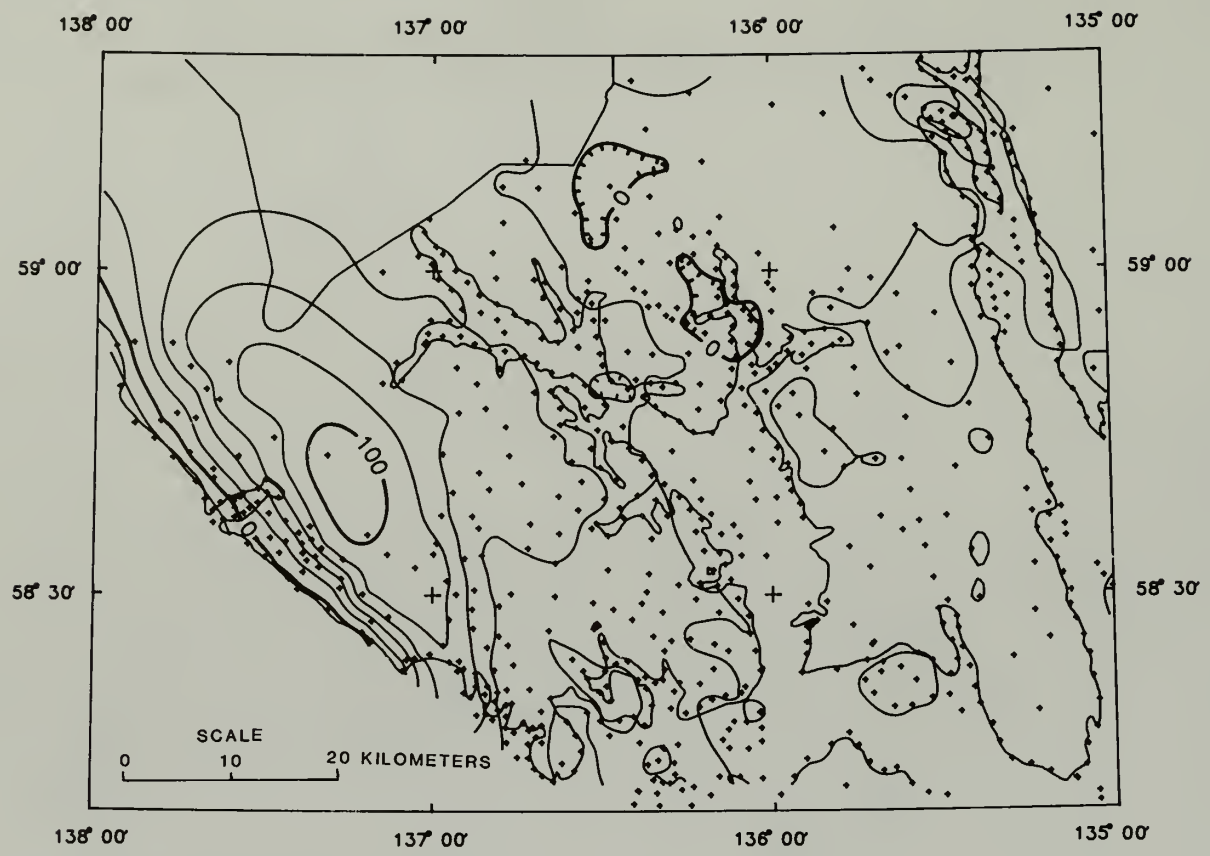

Fig. 2. Isostatic gravity map of Glacier Bay National Park and vicinity, Alaska. Crosses indicate locations of measurements. Contour interval is 20 milligals; hachures indicate gravity lows.

Fairweather Range may have been elevated by as much as 14 km during a period of about 25 million years; this uplift is centered west of that indicated by the tide-gauge data. Clark (1976) used an inverse mathematical analysis to calculate a model of glacial thinning that explained the tidal uplift data. However, his analysis assumed that the uplift is entirely the result of elastic and isostatic response to the glacial retreat. These Glacier Bay uplift rates are about 10 times faster than those measured in Scandinavia, but this may result from the retreat having been relatively recent.

Regional Gravity

Collection of regional gravity data within the Glacier Bay National Park and Preserve began in 1972 with skiff traverses along the bay's shoreline as part of a survey of southeast Alaska (Barnes 1972; Barnes et al. 1975) that was itself part of the reconnaissance study of the whole state (Barnes 1977). Many additional gravity measurements were made in 1976 using both skiff and helicopter transportation during a mineral appraisal of the Glacier Bay National Monument Wilderness Study Area (Brew et al. 1978).

Radar equipment (Watts and England 1976) was used to measure the thickness of ice at gravity measurement sites on glacier surfaces. Most of these measurements were concentrated near the large gabbroic plutons (iron- and magnesium-enriched intrusions) in the western half of the park; they are summarized in Barnes et al. (1978) and Fig. 1. Ice thickness measurements on various western valley glaciers ranged from 99 to 442 m, and three depths on the Brady Glacier were greater than 900 m, indicating glacier bottoms 30 to 250 m below sea level.

The initial gravity plot for Glacier Bay (Barnes et al. 1978) was a simple Bouguer gravity (corrected for latitude, elevation, and attraction of underlying rock) map because terrain corrections had not yet been completed. Digital elevation model (DEM) tapes (Elassal and Caruso 1983) of Alaskan terrain became available later, and preparation of both complete Bouguer (terrain-corrected) and isostatic (gravity also corrected for the effects of thicker crust beneath high topography) gravity maps became possible for most of the state (Barnes 1984a).

The principal features of the new isostatic gravity map of the Glacier Bay region (Fig. 2) are the size of the large positive high in the western part of the park and the abundance and

extent of positive anomalies. The high of +115 mGal (gravitational acceleration unit, 10^{-3} Gal = 10^{-5} m/sec^2) is greater than any anomaly on the isostatic map of the conterminous United States (Simpson et al. 1986). Comparison of the gravity map and the geologic map (Brew et al. 1978) shows that the gravity maximum is clearly correlated with the Mount La Perouse layered gabbroic body. Gravity data suggest that this pluton is more extensive at depth than at the surface and that it has a thickness greater than 6 km. This belt of high gravity also coincides with the zone of maximum uplift (>14 km in 25 million years) on Brew's southeast Alaska vertical-movement map (this volume).

The predominance of positive anomalies on the map may in part reflect a broad free-air gravity high shown by satellite data to extend over much of the Gulf of Alaska and the southern part of the state (Bowin 1985). A small gravity high near the northeast corner of the map and outside the park boundary is caused by a large gabbroic stock beneath the city of Haines (Barnes 1986).

The only negative isostatic anomalies shown on the map are an elongate low shown by a gravity decrease along the west coast and two small lows in the vicinity of Muir Inlet. The west coast low is caused by a sequence of sedimentary rocks of the Yakataga Formation, which thickens offshore. The Muir Inlet lows occur where glacial retreat is now most rapid and where raised beaches indicate the most rapid uplift (Goldthwait 1987). However, these anomalies are too small to represent isostatic depressions at the base of the Earth's crust because their dimensions are smaller than the estimated 30 km thickness of the crust in this part of Alaska (Barnes 1977). Low-density plutons and/or sediment-filled glacial excavations are more probable causes of these gravity lows. The map does not show a relative gravity low that has dimensions similar to, but broader than, the pattern of uplift contours; such a low might represent a crustal depression beneath the ice load and thus an isostatic process.

Temporal Gravity Change

The uplift of the Glacier Bay area has been sufficiently rapid to cause gravity changes that should be measurable over a 10- to 20-year period. These changes should also provide additional information about the geologic processes causing the uplift. Uplift associated with the 1964 earthquake in south-central Alaska caused such a measurable gravity change (Barnes 1966) that Jachens (1978) and Savage (1984) later extended the analysis to other types of crustal deformation.

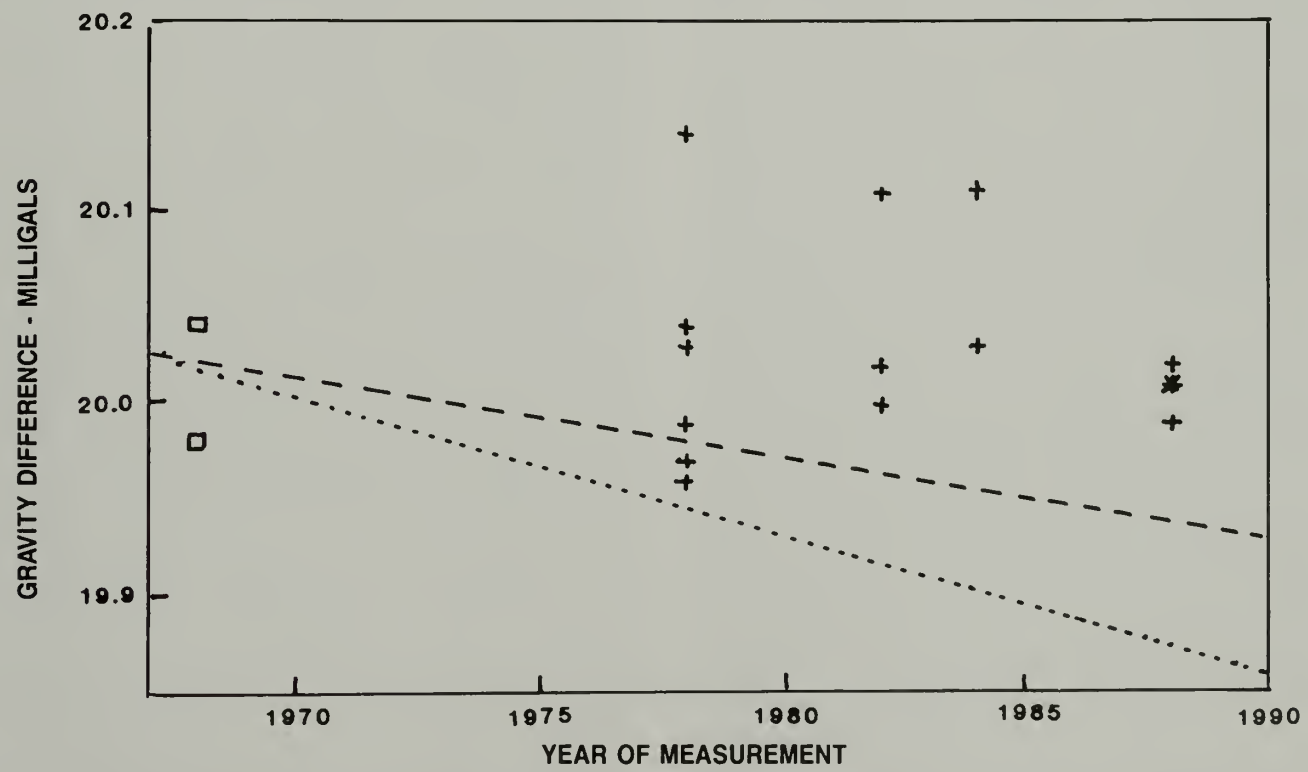

Fig. 3. Graph of measurements of the gravity difference between Juneau and Gustavus airports as a function of year of measurement. Dotted line indicates expected free-air gravity change (no addition of mass beneath uplifted station) of 2.35 cm/year for Gustavus relative to Juneau airport. Dashed line indicates expected Bouguer gravity change with addition of underlying infinite slab of mantle material having a density of 3.10 gm/cm^3.

Measurement and geologic interpretation of the temporal gravity change at Glacier Bay were first discussed by Barnes (1984b), and the now-longer observation period and new data reported here strengthen the earlier conclusion.

Analysis of temporal gravity change in the Glacier Bay area is dependent on the following history of measurements. The earliest gravity measurement near Glacier Bay was made in 1956 by Thiel et al. (1958) on the runway apron at Gustavus airport, but regrading and paving of the runway have made reoccupation of their station impossible. In 1964 the U.S. Coast and Geodetic Survey made three dozen measurements near the bay (Rice 1969) at sites that could be reoccupied, but some of the reported meter drifts were fairly large. The U.S. Geological Survey repeated some of these measurements in 1972, but these also had high drift and thus may be useful only as an indication of the accuracy and future repeatability of the data set.

The best record of the Glacier Bay temporal gravity change began in 1968 with two U.S. Geological Survey measurements of the gravity difference between the Gustavus and Juneau airports. This difference has now been remeasured 15 times over a 20-year period, most recently with four measurements made at the time of this symposium in 1988 (Fig. 3). This series of measurements began when an unexpected bad-weather diversion to Gustavus of a commercial air flight between Juneau and Haines provided the opportunity for the first pair of measurements. The gravity difference for this first pair was 0.06 mGal. The Juneau-Haines difference measured by the two meters on that flight agreed within 0.01 mGal, however. That difference was supported by other measurements made in the same and the following year, suggesting minimal meter drift, so 0.06 mGal was considered to be a good estimate of the possible error of the initial pair of measurements. Twenty years later, the four most recent measurements differed by less than 0.03 mGal, and the mean of these differences is identical to the mean of the initial pair. A least-squares fit to the total set of 17 differences between Juneau and Gustavus suggests a gravity increase of less than 0.0024 mGal/year at Gustavus. The Gustavus station was also tied to Juneau during the 1972 and 1976 field work, but these ties involved marine travel, longer time spans, and higher meter drift, so the results are not included in Fig. 3. These data are nevertheless consistent with the ties made by aircraft travel.

The uplift rates at the Juneau and Gustavus airports are critical parts of the temporal change analysis. The Juneau airport is approximately midway between Auke Bay and Juneau harbor (off Fig. 1 and 4 km southeast of the airport), where Hicks and Shofnos (1965) recorded uplift rates of 1.91 and 1.31 cm/year respectively, so the airport uplift is assumed to be 1.61 cm/year. Gustavus airport is assumed to be rising at the same rate as Bartlett Cove or 3.96 cm/year, although a linear interpolation of changes between there and Swanson Harbor to the southeast (1.58 cm/year) suggests that the Gustavus uplift may be as low as 3.49 cm/year. The uplift rate of Gustavus airport relative to Juneau airport is thus calculated to be 2.35 cm/year, giving a total uplift of 47 cm over a 20-year period. Such an uplift amount would, according to the free-air gravity gradient (assuming the addition of no mass at depth), cause a total gravity decrease of 0.145 mGal in the 20-year period, giving a gravity decrease rate of 0.007 mGal/year (dotted line Fig. 3). If, on the other hand, this uplift is caused by an isostatic process involving the addition of an infinite slab of subcrustal material having a density of 3.10 gm/cm^3, then the 20-year Bouguer change would be 0.08 mGal (dashed line, Fig. 3). These data suggest that even more mass has been added below the Gustavus airport station. Possible complications, such as changes in water table, are considered unlikely because both Juneau and Gustavus airports are less than 3 km from the ocean and 12 m above mean sea level.

Jachens' (1978) graph of the ratio of gravity change to elevation change for different processes of crustal deformation suggests a possible cause for such an unmeasurable gravity change; it is a process involving elastic compression of the earth's crust having a Poisson's ratio close to 0.25. The gravity-change data thus can be interpreted to suggest accumulating elastic strain in the Glacier Bay region. This strain is possibly related to transgressional northward movement of the Pacific plate and to motion on the Fairweather-Queen Charlotte fault systems. This interpretation is consistent with other evidence of tectonic activity, such as the prevalence of earthquakes near the northern rim of the park (Horner 1983). Continued accumulation of data may show, however, that the uplift is really a combination of both isostatic and tectonic processes.

Juneau is within the broad zone of regional uplift, but it is well outside the area of most rapid uplift and most rapid glacial retreat, so the Juneau-Gustavus gravity difference should provide a good indication of any change caused by an isostatic component of the uplift. A gravity change at Juneau itself is best measured by studying the gravity difference between Juneau and Ketchikan, nearly 400 km to the southeast, which tidal data show is almost stable. However, this difference is difficult to measure because of both the magnitude of the gravity interval and the changes in air route caused by construction of a new airport at Ketchikan. Fifteen ties involving four air terminals now indicate a small gravity decrease at Juneau over a 25-year period. These data may suggest a free-air gradient uplift without the addition of an underlying mass at Juneau, but their large scatter makes continued evaluation desirable.

Problems and Recommendations

Tidal data provide the principal evidence for the uplift in the Glacier Bay region, but many of these data are based on observation periods of less than one summer in duration. Further, the measurements have been repeated only once after an interval of about 20 years at the stations showing the larger uplifts. The Bartlett Cove tidal data were discarded by Clark (1976) because of the lack of a continuous tidal record and possible benchmark subsidence during a 1958 earthquake. These data-acquisition problems would be alleviated with a continuously recording tidal gauge at the park headquarters that would also aid in the interpretation of short-term records within Glacier Bay. The 20-year period that provided the most important data for the 1959 study has now been extended to 50 years, so repeated field observations and reexamination of the tidal data seem desirable. Such additional studies should include occupation of the tidal observation points on the west coast of the Park, which were neglected in the initial study.

The temporal gravity-change data are now confined to relative measurements of the gravity difference between Juneau and Gustavus airports; but airport construction frequently destroys the stations at which such measurements are made, and multiple ties are always needed. High-precision absolute gravity measurements can now be made by free-fall apparatus, and such measurements should be scheduled regularly at Bartlett Cove. In 1987 such a measurement was made at Haines (Sasagawa et al. 1989), but a measurement at Bartlett Cove would show any change more rapidly and would provide a better base for gravity measurements relative to those in other parts of the uplift area.

The U.S. Geological Survey's network of base stations for the 1972 and 1976 shoreline surveys (Fig. 1) provides a set of multiple-occupied stations with established accuracy and reproducibility. These stations should be reoccupied to provide areal coverage of the gravity change once an absolute measurement is made at Bartlett Cove. Such studies should be coordinated with other crustal strain research, such as electronic-distance-measurement (EDM) trilateration, global positioning satellite system (GPSS) observations, and seismicity measurements.

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Physical Factors Influencing Stream Development in Glacier Bay National Park, Alaska

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Abstract

Channel morphology, riparian vegetation, and sediment transport were examined in five streams of different ages in Glacier Bay National Park where rapid retreat of glacial ice has exposed a chronosequence of landscapes. The youngest stream, Wolf Point Creek (study reach deglaciated around 1955), is fed by glacial ice and had the highest suspended sediment concentrations of any of the streams studied (103-111 mg/L at baseflows). The main channel of Wolf Point Creek was relatively stable because of the peak flow buffering effects of the lake associated with the remnant glacier. However, the floodplain was periodically inundated and only sparsely vegetated and highly braided. Morphometric characteristics and changes in Nunatak Creek (study reach deglaciated around 1950) indicate an unstable system with some thalweg expression and bank aggradation. About 100 years after deglaciation (Ice Valley stream), woody riparian vegetation begins to stabilize stream banks and becomes established on gravel bars where it provides potential sites for incipient woody debris jams. The increased accumulation of woody material and the subsequent colonization of gravel bars by alder and willow probably increase channel stability and pool formation in Berg Bay South (deglaciated around 1830). Berg Bay North, a stream of similar age to Berg Bay South, stabilized more rapidly because of the buffered peak flows and greater sediment trapping efficiency attributed to the lakes and bogs present in this system. Thalwegs of clearwater streams without lakes deepen through the progression of stream ages. Sediment loads tend to decrease with stream age, and floodplains become less braided and more stable.

KEY WORDS: Stream development, suspended sediment, woody debris, postglacial streams, deglaciation, thalweg, riparian vegetation, bank erosion, braiding.

Sediment transport in glacial meltwater streams has been investigated in a number of geographic regions (e.g., Ostrem 1975; Hammer and Smith 1983; Tomasson 1985). However, there have been few opportunities to evaluate changes in sedimentation and channel development following deglaciation. These changes appear to be critical to the early stages of biotic community development in postglacial streams (Milner 1987; Milner and Bailey 1989). The rapid retreat of glacial ice in Glacier Bay provides a unique opportunity to examine the changes in sediment transport and channel morphology, as well as the interaction of riparian vegetation with these factors as streams develop. Five streams along a chronosequence in Glacier Bay National Park were selected to evaluate the role of time on the development of postglacial streams. The streams range in age from Wolf Point Creek, a young drainage largely deglaciated about 34 years ago, to a pair of streams at Berg Bay deglaciated about 160 years ago (Fig. 1). Stream reaches of 100 to 200 m in length were selected for detailed investigation to correspond to previous studies of community development (Milner 1983, 1987).

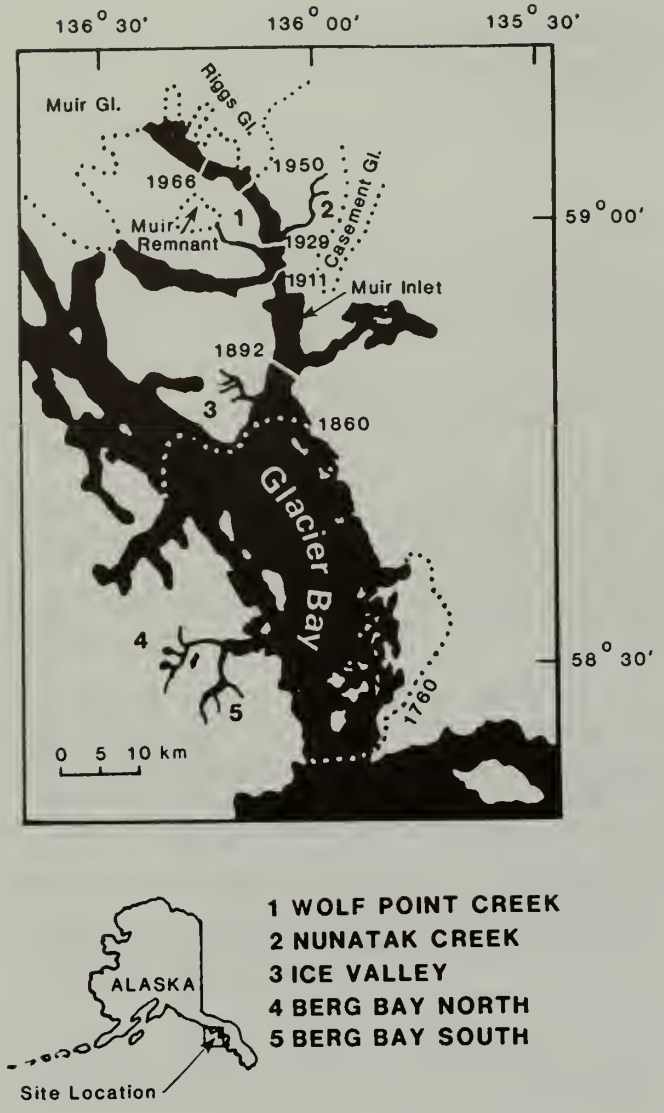

Fig. 1. Locations of study streams in Glacier Bay National Park with respect to position of retreating ice mass.

Wolf Point Creek

The study reach of Wolf Point Creek (Fig. 2), the youngest stream in the chronosequence, was free of glacial ice in 1955 (W.O. Field, personal communication 1983). The stream is still fed by the Muir remnant ice sheet and thus transports considerable glacial silt. The stream originates from a meltwater lake in front of the remnant glacier, cuts through bedrock, and then flows over glacial moraine, till, and outwash deposits. The floodplain in the lower reach is highly braided with only scattered riparian vegetation consisting largely of early colonizers such as fireweed *(Epilobium latifolium)* and *Dryas drummondii*. In the last several years, an increasing number of alder *(Alnus crispa)* seedlings have begun to establish along the more stable portions of the floodplain. More mature stands of alder occupy the upper terraces along Wolf Point Creek.

Peak flows in Wolf Point Creek appear to be somewhat attenuated because of the buffering effects of the meltwater lake. However, when overbank flows occur, the intermittent channels in the floodplain shift readily because of the absence of both riparian vegetation and large woody debris.

During a three-year period of monitoring, channel changes in Wolf Point Creek were slight. There was no thalweg deepening, bank aggradation, or pool formation. The average width/depth ratio was 32 for the active channel, the highest ratio for all five study streams.

Concentrations of total suspended solids (TSS) during baseflows ($< 2 m^3/s$) were highest in summer and autumn (103-111 mg/L) and lowest in winter and spring (3.4-31 mg/L). This pattern corresponds to the seasonal melting and subsequent release of fine sediment from the Muir remnant at the headwaters of Wolf Point Creek. For most all discharges sampled, Wolf Point Creek had the highest TSS levels of all five study streams. Comparison of a suspended sediment sample collected during a major autumn stormflow (TSS=229 mg/L) to a sample collected earlier in autumn during a moderate flow (TSS=235 mg/L) suggests that moderate to high autumn flows may sequentially deplete the available supply of fine sediment released by meltwater during the summer months. The relatively high suspended sediment levels in Wolf Point Creek have thus far deterred colonization of this stream by salmonids.

Nunatak Creek

The lower reaches of Nunatak Creek were free of glacial ice by the early 1940s (Field 1947). The study reach (Fig. 3), about 2 km upstream of a large braided depositional area, was probably free of ice by 1950. The stream is largely fed by snowmelt from surrounding mountains augmented by runoff from two small kettle lakes (Milner 1983). Large fluctuations in discharge can occur during autumn storms and spring snowmelt.

The channel system is unstable and is typified by the study reach where the stream cuts through deposits of glacial out wash and till. Steep eroding channel banks are up to 15 m high. Braided depositional regions and zones of extensive scour occur within the system. The lower terraces of the floodplain are beginning to become vegetated with *Dryas* and lesser amounts of alder and willow *(Salix* spp.). The upper terraces support a well-coalesced mat of *Dryas* with interspersed alder and willow.

Channel changes measured at Nunatak Creek during a 3-year period are indicative of an unstable system that is just

Fig. 2. Photograph of study reach of Wolf Point Creek.

beginning to show signs of development. All four cross-sections monitored at Nunatak Creek showed evidence of thalweg deepening, up to 36 cm. Several cross-sections showed signs of channel constriction and bank building. The east braid by the point bar at cross-section 1 filled in approximately 55 cm between 1982 and 1985; by 1988 this braid had disappeared. The contribution of riparian vegetation to channel stability is minimal, and there is virtually no large woody debris in the channel (Fig. 3). The incipient pool development that is occurring around large boulders should improve rearing habitat for juvenile salmonids. Coho salmon *(Orcorhynchus kisutch)* and Dolly Varden charr *(Salvelinus malma)* have colonized Nunatak Creek.

The average concentration of TSS in nine composite samples collected during summer and autumn baseflows ($< 4 m^3/s$) was 4.6 mg/L; concentrations in individual samples ranged from 2 to 8 mg/L. Moderate spring flows at Nunatak Creek (2.6 m^3/s) contained higher TSS (35 mg/L) than similar flows during summer and autumn (3.3 to 6.5 mg/L). This is the reverse of the seasonal pattern observed at Wolf Point Creek. In Nunatak Creek, it appears that sediment stored in the channel during early winter prior to freezing is released during spring thawing and ice breakup. In addition, ice breakup can scour stream banks and bottom sediment. The only stormflow sampled (26.3 m^3/s) had a similar TSS concentration (223 mg/L) to a sample taken from Wolf Point Creek during the same storm. For all samples except the October 1984 peakflow, organic suspended solids were < 3 mg/L.

Ice Valley

The study reach of the stream in the lower portion of Ice Valley (Fig. 4) was deglaciated by approximately 1885 (Field 1947). The channel cuts through thick deposits of glacial outwash creating banks up to 20 m in height (Sidle 1985). Snowmelt from higher elevations provides most of the baseflow in this system. During winter and early spring, channel flow often disappears into permeable gravel outwash in the lower reach. The numerous gravel bars within the channel are slowly becoming stabilized by colonizing alder

Fig. 3. Photograph of study reach of Nunatak Creek.

and willow. In general the stream is less braided than either Wolf Point Creek or Nunatak Creek (Fig. 4). Scattered Sitka spruce *(Picea sitchensis)* trees are beginning to invade alder thickets adjacent to the upper banks.

During two years of monitoring, there was evidence of minor channel deepening in all three monitored cross-sections. The point bar in the upstream portion of the study reach eroded 13 to 20 cm during the two years. The channel appears to be adjusting and will eventually fill in one of the braids. Most of the flow is confined to the main channel with almost no braiding in the floodplain.

Levels of TSS during summer and autumn baseflows (< 2 m^3/s) were always < 5 mg/L and averaged 1.9 mg/L for five composite samples collected over two years. No samples were collected during spring flows. One sample collected during a moderate flow (3.8 m^3/s) had 10.5 mg/L TSS.

Ice Valley appears to represent the stage of stream succession where the riparian vegetation is beginning to affect channel morphology. Alder and willow saplings growing along the upper banks become dislodged by bank erosion and occasionally establish along gravel bars and backwater areas. Small dams of woody debris are then trapped behind these alder and willow clones. During high flows, many of these incipient woody debris dams are flushed out of the system; however, the few clumps that establish appear to eventually develop into large woody debris dams, a major stabilizing and sediment storage component in forest streams in coastal Alaska (Sidle 1985, 1988).

Berg Bay

The area around Berg Bay was free of glacial ice around 1830 and represents the oldest segment of the chronosequence studied in Glacier Bay. Two streams in this area were investigated: (1) Berg Bay South -- a 6.5 km long stream not associated with any lakes in the drainage basin (Fig. 5), and (2) Berg Bay North -- a 8.0 km long stream influenced by and directly connected to several lakes (Fig. 6) (Milner 1987).

Berg Bay South is the more dynamic of the two channels largely because it is subject to higher peak flows. Some channel braiding occurs in the floodplain as well as evidence

Fig. 4. Photograph of study reach of stream in Ice Valley.

of shifting gravel bars (Fig. 5). Higher elevation terraces are being stabilized by mature stands of alder and cottonwood *(Populus trichocarpa)* that are beginning to give way to Sitka spruce. Large woody debris is an important stabilizing component at this stage of stream development. Mature alder and cottonwood that fall into the channel are transported by high flows or lodged against banks where they provide a matrix for relatively stable woody debris dams. Saplings can then sprout from the root wads and stems of fallen trees, adding more stability. Debris dams in Berg Bay South are more stable, larger, and more numerous than those in Ice Valley.

Lakes in the Berg Bay North systems appear to have influenced stream development by attenuating peak flows and by allowing a stable stand of Sitka spruce to develop along the channel. The stream has evolved with stable pools developed downstream of moss-covered boulders. Little evidence of streambank erosion or associated treefall into the channel exists, and the spruce stand that encroaches up to the channel has not been flooded in recent years.

Channel changes measured along several cross-sections in these two streams supported our general field observations. Portions of the Berg Bay South channel experienced thalweg deepening and migration. The backwater area in the study reach is beginning to fill in. The influence of large woody debris on sediment deposition is evident. The upstream gravel bar appears to be expanding toward the east channel bank (Fig. 5). Bank building was also evident in some locations. In contrast, the main channel of Berg Bay North experienced little scour or fill during the three years of monitoring. However, the Equisetum bog adjacent to the channel (Fig. 6) acted as a fine sediment trap, filling an average of 14 cm during the three years.

Both Berg Bay South and North had low TSS levels (≤ 4 mg/L) during summer baseflows (< 1.3 m^3/s). Elevated TSS levels (18 to 23 mg/L) were found in both streams during moderate spring flows (2.6 to 3.9 m^3/s), probably related to the release of sediment stored in each system during winter and eroded during ice breakup. During an autumn storm in 1984, Berg Bay South had higher TSS (19 to 33 mg/L) than Berg Bay North (5 mg/L), indicating the greater stability of the Berg Bay North system.

Fig. 5. Photograph of study reach of Berg Bay South.

Fig. 6. Photograph of study reach of Berg Bay North.

Differences between Berg Bay South and North are reflected in fish populations: densities of juvenile coho were six times higher in Berg Bay North than in Berg Bay South (Milner and Bailey 1989). The more dense canopy cover, together with the narrower, more stable channel and floodplain at Berg Bay North, are largely responsible for these differences. Aquatic habitat in Berg Bay South is improving with the recruitment of woody debris and subsequent stabilization of gravel bars and pool formation.

Summary of Stream Development

Development of postglacial streams into forest streams in coastal Alaska involves complex interactions among the fluvial system, riparian vegetation, and geomorphic processes in the watershed. The youngest stream in this study, Wolf Point Creek, is characterized by high sediment loads that exhibit cyclical patterns because of contributions from the remnant glacier. There was no evidence of channel develop ment, although the main channel was relatively stable due to the buffering of peak flows by the proglacial lake. Slightly older Nunatak Creek is an unstable system just beginning to show signs of thalweg expression and bank building. The only pools found in either youthful stream were in quiescent areas downstream of large boulders. Suspended sediment levels in Nunatak Creek were significantly lower than in Wolf Point Creek. Riparian vegetation in both of these youthful systems is sparse. However, the colonization of floodplains by nitrogen-fixing *Dryas* is a precursor of more stabilizing woody vegetation.

About 100 years after deglaciation, developing woody riparian vegetation begins to stabilize stream banks and establishes on gravel bars in the channel, thus providing incipient sites for woody debris dams. Ice Valley is an example of an early stage of a developing forest stream. As time passes, more mature riparian stands of alder, willow, and cottonwood gradually give way to Sitka spruce. In Berg Bay South (deglaciated around 1830), larger trees in the riparian zone continue to be recruited into the actively eroding reaches of the stream. This larger woody debris forms more stable features than in Ice Valley. These debris dams promote the establishment of woody vegetation on formerly unstable gravel bars and floodplains. Pools are formed around these channel roughness elements. Streams associated with lakes, such as Berg Bay North, appear to stabilize much more rapidly than streams without lakes. In all clearwater streams, spring flows had the highest suspended sediment levels, probably caused by ice breakup and related scouring and the release of sediment stored in the channels during the winter months. Minimum substrate size in both the channel and floodplain tended to increase with stream age, indicating that older streams were becoming more stable.

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Groundwater Flow Systems and Geochemistry near the Margin of the Burroughs Glacier

by

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Abstract

Groundwater and meltwater in recently deglaciated areas at the margin of the Burroughs Glacier and in areas deglaciated over 40 years ago near Wachusett Inlet were sampled to determine the evolution of groundwater geochemistry. Dominant ions were Ca and HCO_3 in a consistent molar ratio of 1:2, suggesting that calcite is the predominant mineral dissolved in glacial sediment composed primarily of igneous and metamorphic lithologies. Groundwater pH averaged 8.3 and was generally in equilibrium with calcite, dolomite, and quartz. Average log P_{CO_2} values in groundwater were near atmospheric values, although a trend from lower values (-4.22) near the ice margin to higher values (-2.83) at downstream discharge points on the Burroughs River was observed. This trend, and the accompanying increase of Ca and HCO_3, is best explained by the establishment of vegetation on deglaciated surfaces and subsequent addition of CO_2 to the system. Higher concentrations of cations (particularly Mg and Na) in groundwater than in precipitation suggests that silicate minerals are also weathering. Poor correlations of these cation concentrations with H_4SiO_4 concentrations suggest nonequilibrium conditions and may reflect rapid exchange of H^+ for cations on clay minerals. All of these reactions occur within residence times of less than five years, based on estimates of hydraulic conductivity, groundwater velocity, and flow path lengths. Although the exact chemical evolution along a single groundwater flow path is not known, groundwater appears to change chemically from a calcium sulfate water near the ice margin to a calcium bicarbonate water near Wachusett Inlet. This trend reflects both an increase in HCO_3 concentration and decrease in SO_4 concentration. Differences in the sulfur content of till, a change in the rate of sulfate production over time, or removal of sulfate from the till, perhaps by groundwater or vegetation, are possible causes for this trend.

KEY WORDS: Glacier Bay, groundwater, geochemistry, glacial till, calcite dissolution, chemical weathering.

The effect of vegetation and residence time on the groundwater geochemistry and its evolution in an area undergoing rapid deglaciation near the Burroughs Glacier was investigated. The Burroughs Glacier area was chosen because the physical and chemical weathering, development of early groundwater flow systems, and evolution of groundwater geochemistry may also be analogous to the processes that occurred after the retreat of late Wisconsin ice in hilly regions of the Midwest and New England. Data from this study will improve our understanding of groundwater geochemistry in modern glacial environments and also in areas where fresh, unweathered materials are exposed to the weathering process.

Recently deposited glacial sediment represents a youthful hydrogeological and geochemical system. Studies of the hydrogeologic properties and geochemical signatures of such a system may additionally provide insight into the present day character of groundwater in Pleistocene glacial sediment. This is particularly true in fine-grained aquitards where Pleistocene-age groundwater has been identified solely by interpretation of stable and radioactive isotope data (e.g., Simpkins 1989).

The Burroughs Glacier, located within Glacier Bay National Park and Preserve, is a stagnant remnant of a larger, active Neoglacial ice mass (Fig. 1). The entire glacier now lies below the equilibrium line and is downwasting rapidly (Mickelson 1986a,b); approximately 600 m of ice has ablated since the 1890s. Like many glaciers in similar topographic settings, the hilltops are exposed early in the deglaciation process and the last residual ice masses are in the valley bottoms. The glacial history and landform genesis at the southern margin of the glacier are analogous to deglaciation history and landform genesis in certain parts of New England

and the upper Midwest (Mickelson 1971; Goldthwait and Mickelson 1982).

Igneous and metamorphic rocks predominate in outcrop and in the glacial sediment in the study area. Rock outcrops of gneiss, dacite and metasediment are present in the vicinity of the glacier. Pebble counts in the till indicate about 11% granite, 11% syenite, 22% and 17% acidic dike rocks and 35% metasiltstones. The less-than-200 mesh (0.075 mm) fraction of the Glacier Bay till contains small amounts of calcite (0.3 to 7.5 percent by weight) and dolomite (0.2 to 1.7 percent by weight) (24 samples; Mickelson 1971).

The glacial environment provides a unique opportunity in which to study initial physical and chemical weathering of glacial sediment and sediment-water interaction. Physical weathering is rapid, and freshly ground, fine-grained particles of large surface area are constantly exposed; initial alteration of these fresh surfaces will greatly influence water chemistry (Drever 1982). Abundant rainfall, approximately 200 cm/year at Bartlett Cove (Hartman and Johnson 1978) and slightly less at Wachusett Inlet, enhances the weathering process.

A number of researchers have recently discussed the chemical composition of subglacial, supraglacial and proglacial meltwater in relation to discharge (Rainwater and Guy 1961; Collins 1979; Eyles et al. 1982; Raiswell 1984; Raiswell and Thomas 1984; Thomas and Raiswell 1984) and to bedrock lithology (Reynolds and Johnson 1972; Slatt 1972). Geochemistry of groundwater in glacial environments has largely been ignored, except for a brief mention by Raiswell (1984).

Methods

During June 1986 and August 1987, groundwater flow systems developed in the till near the southeastern margin of the Burroughs Glacier were investigated. Numerous zones of groundwater discharge were observed, and these were marked by arcuate re-entrants and springs along the southern shore of the proglacial Burroughs Lake (sample numbers 2, 7, and 9; Fig. 1). Springs discharged at a flow rate of approximately 0.05 L/sec and may be fed by precipitation or snowmelt that recharges the till near the nunatak crests and at any point downslope from the nunataks. Groundwater presumably flows through the till or at its base, so that the till/bedrock interface is a no-flow boundary. Many of these flow systems may have developed before deglaciation, as the ice wasted downward into the valleys. Farther south and downstream, the Burroughs River acts as a groundwater divide and groundwater discharges into it from both sides of the river. In the context of the deglaciation history (Fig. 1),

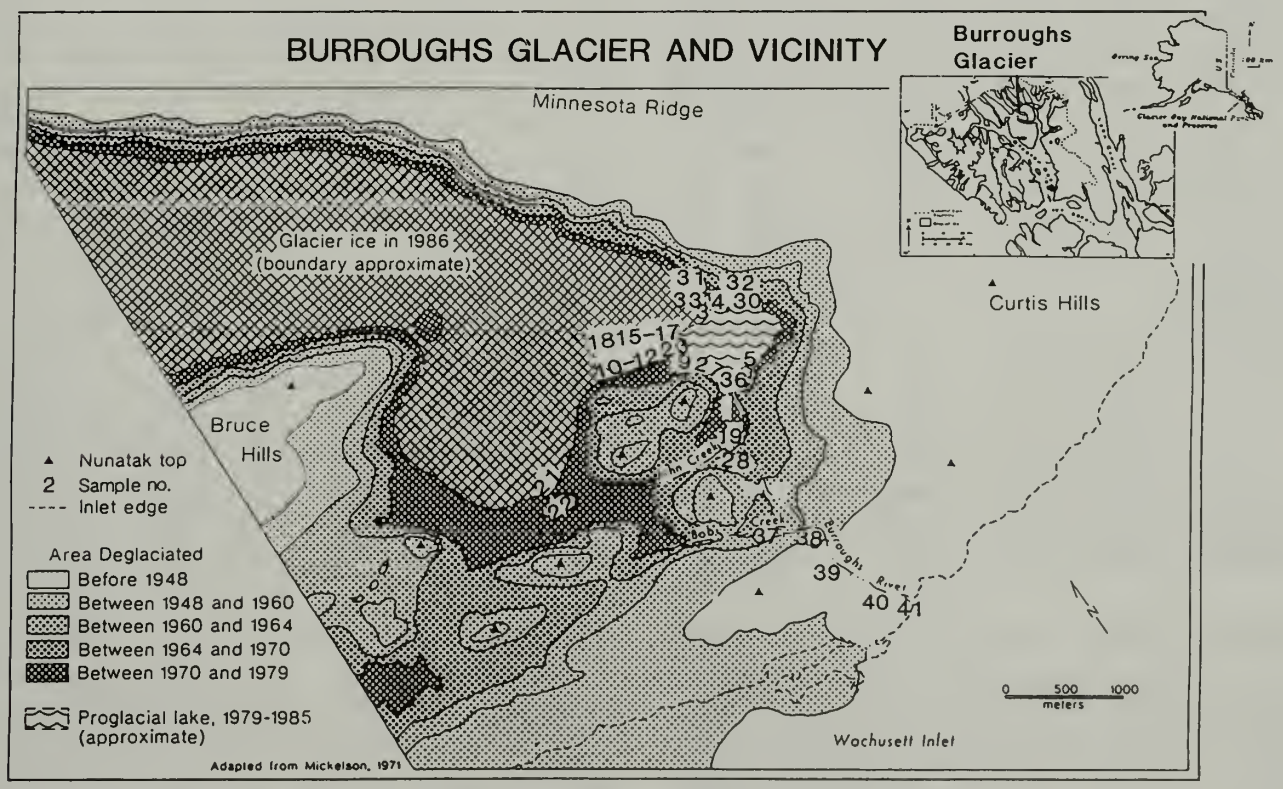

Fig. 1. The Burroughs Glacier area and sample sites in the study area.

Table 1. Analytical concentrations of all samples in the study area.

				CATIONS (mmoles/L)				ANIONS (mmoles/L)				
Sample No.	pH	Temp. (C°)	Cond. (as a-l)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	PO_4	H_4SiO_4
Rainwater												
19	6.05	9.6	12	0.01		0.04	0.02		0.02	0.07		
Glacial Ice												
12	9.06	9.1	23	0.07		0.05	0.02	0.17	0.06	0.03		0.03
18	6.78	8.0	24	0.07	0.03	0.03		0.20	0.01	0.03	0.01	0.37
20	7.22	8.8	8	0.03				0.04		0.03		
21	7.15	13.8	1	0.01				0.01				
33	7.07	15.0	30	0.12	0.01	0.04		0.25		0.04		0.18
MEAN	7.45	10.9	17	0.06	0.02	0.04	0.02	0.14	0.03	0.03	0.01	0.20
Meltwater												
3	8.94	4.0	24	0.10	0.01			0.18	0.02			0.07
4	8.59	12.7	90	0.38	0.02	0.05		0.70	0.09			0.05
5	9.09	5.8	28	0.12	0.01			0.18	0.03			0.03
10	8.99	3.8	53	0.22	0.02	0.06		0.50	0.01		0.01	0.25
11	9.30	2.8	52	0.21	0.02	0.05		0.50	0.01		0.01	0.21
15	9.04	2.3	23	0.11				0.17		0.04		0.07
16	9.18	2.3	17	0.08				0.13		0.03		0.06
17	8.13	3.0	4	0.02				0.04				0.05
22	8.52	9.1	85	0.36	0.01	0.00		0.53	0.12			0.05
28	8.08	7.4	39	0.17	0.01			0.24	0.05			0.04
30	8.40	12.9	112	0.48	0.03	0.04		0.94	0.09	0.01		0.07
31	8.97	6.0	44	0.19	0.01	0.03		0.37	0.02			0.12
32	8.16	10.4	27	0.12	0.01			0.27				0.14
34	8.67	5.7	15	0.08				0.14				0.06
38	8.17	12.1	102	0.41	0.02	0.05		0.59	0.17	0.01		0.04
41	8.32	9.4	41	0.16	0.01	0.04		0.24	0.04	0.04		0.04
MEAN	8.65	6.9	47	0.20	0.02	0.04		0.36	0.06	0.03	0.01	0.08
Groundwater												
2	8.76	12.9	243	0.87	0.08	0.22	0.04	1.11	0.55	0.03		0.16
7	8.55	11.1	315	1.16	0.11	0.21		1.14	0.88			0.17
9	8.78	8.2	232	0.76	0.06	0.32	0.02	0.78	0.64	0.03		0.12
36	7.71	12.8	479	2.21	0.09	0.12		3.13	0.81			0.10
37	8.19	11.9	354	1.48	0.07	0.10	0.03	2.03	0.72	0.01		0.10
39	8.44	11.2	161	0.62	0.05	0.13		1.15	0.22	0.04		0.08
40	7.96	11.3	295	1.32	0.05	0.16	0.02	2.67	0.20	0.03		0.11
MEAN	8.34	11.3	297	1.20	0.07	0.18	0.03	1.72	0.57	0.03		0.12

Blank values indicate concentrations below detection limit.

groundwater ideally recharges in the oldest sediment and encounters progressively younger sediment closer to its discharge point (Fig. 1). However, groundwater flow systems are older, have longer residence times, and are more affected by vegetation and accompanying CO_2 input in areas southward along the Burroughs River toward Wachusett Inlet.

Piezometers consisting of 19 mm (I.D.) ASTM Schedule 80 PVC standpipes with 203 mm (length), factory-slotted (0.25 mm slots) screens were installed in a nested configuration to depths of 1.5 m along the Burroughs Lake shore-

line. Hydraulic head gradients were measured, and the existence of upward head gradients and groundwater discharge was verified. Sediment samples were collected for grain size analysis, and single-well response (slug) tests were conducted to estimate hydraulic conductivity (K) and groundwater residence times.

Water samples were also collected from the piezometers and springs and also from other water sources (e.g., precipitation, meltwater and ice) in and adjacent to the glacier (Fig. 1) as part of a larger study (Simpkins 1988). Data from those environments are listed here to provide comparison to groundwater geochemistry. Sampling from the piezometers proved difficult, hence springs were artificially created by digging into the sediment until fine sediment settled and a steady flow of water ensued. Standard techniques of field pH and temperature measurement and water sampling (Wood 1981) were used, and till samples were collected for chemical analysis.

Results

Estimates of hydraulic conductivity (K) of the till, which are necessary to estimate groundwater residence time, were obtained by two methods. Grain size analysis provides an indirect estimate of hydraulic conductivity. Basal till samples collected in this study at the margin of the Burroughs Glacier yielded a composition of 57% sand, 36% silt and 7% clay, which is exactly the mean value found earlier by Mickelson (1971). One sample near a spring contained 86% sand, 11% silt and 4% clay and may reflect washing of fines due to spring discharge. Based on hydraulic conductivity data from till units in Wisconsin (Rodenbeck et al. 1987), estimates of hydraulic conductivity for sediment of this grain size distribution should range from 10^{-5} to 10^{-7} ms^{-1}. A slug test in a piezometer near groundwater sample 2 (Table 1) yielded a value of 10^{-6} ms^{-1}, which is in good agreement with estimates based on grain size. Based on this value of hydraulic conductivity and the estimated maximum flow path lengths of 150 to 250 m, groundwater residence times are probably less than five years.

Concentrations of major elements and major ions for all water samples on and adjacent to the Burroughs Glacier are given in Table 1. Most water samples are characterized by high field pH values (7.96 to 9.09) and very low solute concentrations, a characteristic noted in meltwater from glaciers elsewhere (Slatt 1972; Souchez and Lorrain 1984). Groundwater samples show the lowest pH values (mean=8.34), highest specific conductance (mean=297 microsiemens/m), and highest concentrations of all cations and anions. Mean values of Ca, Mg, Na, K, HCO_3, SO_4, Cl, and H_4SiO_4 are 1.20, 0.07, 0.18, 0.03, 1.72, 0.57, 0.03, and 0.12 mmoles/L, respectively.

The Piper trilinear diagram (Fig. 2) depicts the different water types sampled according to hydrochemical facies and

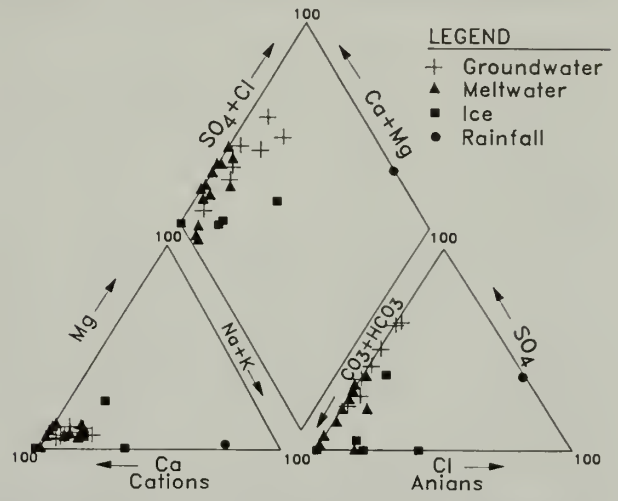

Fig. 2. Piper trilinear diagram showing percentages of cation and anion milliequivalents for all samples in the study area. Groundwater changes from a calcium sulfate to a calcium bicarbonate water with increasing distance from the ice margin.

shows that, except for precipitation and some groundwater, most samples plot well within the calcium bicarbonate hydrochemical facies. The change in groundwater geochemistry from calcium sulfate near the ice margin (samples 2,7 and 9) to predominantly calcium bicarbonate away from the ice margin (samples 36-40) can clearly be seen in the diagram and is further illustrated in Figure 3.

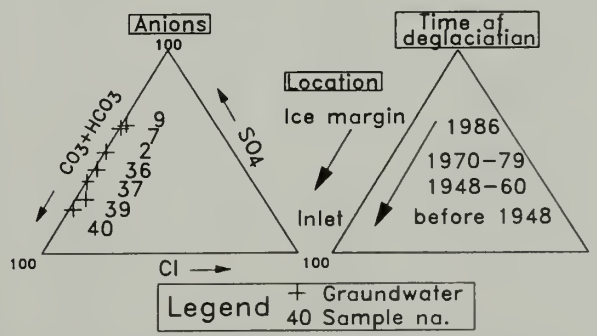

Fig. 3. Diagram demonstrating change in groundwater geochemistry from a calcium sulfate to a calcium bicarbonate water with increasing distance from the ice margin and increasing time since deglaciation.

The program WATEQ4F (Ball et al. 1987) was used to determine the species in solution and the saturation state of the water with respect to solid mineral phases. The saturation index of a mineral (SI) is the logarithm of the ratio of the ion activity product (IAP) to the equilibrium solubility product (K) at the sample temperature (T): SI = log[IAP (T)/K(T)]. The value of the saturation index indicates

Table 2. Calculated P_{CO_2} and saturation indices from WATEQ4F (Ball et al., 1987).

Sample No.	Log P_{CO_2}	SI Calcite	SI Dolomite	SI Quartz
Rainwater				
19	-4.35	-4.33	N/A	N/A
Glacial Ice				
12	-5.17	-1.07	N/A	-0.22
18	-2.78	-3.23	-7.07	0.86
20	-3.85	-3.72	N/A	N/A
21	-4.28	-5.02	N/A	N/A
33	-2.93	-2.53	-6.38	0.43
MEAN	-3.80	-3.11	-2.69	0.21
Meltwater				
3	-5.04	-1.08	-3.48	0.21
4	-4.28	-0.14	-1.65	-0.11
5	-5.17	-0.80	-3.13	-0.20
10	-4.66	-0.30	-1.79	0.75
11	-5.01	-0.05	-1.33	0.69
15	-5.16	-1.00	N/A	0.24
16	-5.44	-1.44	N/A	0.17
17	-4.82	-3.13	N/A	0.04
22	-4.10	-0.40	-2.36	-0.08
28	-4.00	-1.50	-4.51	-0.07
30	-3.71	-0.10	-1.52	0.03
31	-4.75	-0.44	-2.26	0.39
32	-4.03	-1.46	-4.03	0.34
34	-4.85	-1.53	N/A	0.12
38	-3.69	-0.60	-2.65	-0.16
41	-4.23	-1.26	-3.91	-0.15
MEAN	-4.46	-0.95	-2.04	0.14
Groundwater				
2	-4.04	0.50	-0.11	0.39
7	-3.81	0.39	-0.36	0.45
9	-4.22	0.25	-0.80	0.36
36	-2.51	0.28	-0.93	0.19
37	-3.19	0.41	-0.59	0.23
39	-3.67	0.09	-1.06	0.12
40	-2.83	0.27	-0.96	0.27
MEAN	-3.47	0.31	-0.69	0.29

whether the solution is undersaturated (negative SI), supersaturated (positive SI), or at equilibrium (SI=0) with respect to that mineral phase. The theoretical CO_2 partial pressure (P_{CO_2}) of a hypothetical coexistant gas phase with which the water sample is in equilibrium is calculated in WATEQ4F using pH and the HCO_3 concentration. Calculated log P_{CO_2} values and SI values, with respect to calcite, dolomite, and quartz, are listed in Table 2.

Lowest log P_{CO_2} (mean=-4.56 bar) and more negative $SI_{calcite}$ (mean SI=-0.95) and $SI_{dolomite}$ (mean SI=-2.09) values are characteristic of samples from meltwater streams draining the ice or from streams draining recently deglaciated surfaces. In contrast, groundwater samples show the highest P_{CO_2} values (mean=-3.47 bar), much closer to the accepted mean atmospheric log P_{CO_2} values of -3.50 bar, and they show a general trend from lower values near the ice margin to higher values downstream on the Burroughs River (Fig. 1; Table 2). Groundwater is slightly oversaturated with respect to calcite (mean SI=+0.313) and slightly undersaturated with respect to dolomite (mean SI=-0.680). All samples appear in near equilibrium with quartz.

Discussion

Chemical Weathering

Chemical weathering of minerals is occurring in sediment deposited by the Burroughs Glacier. A strong correlation (r^2 = 0.93) and near 1:2 molar ratio between Ca and HCO_3 (Fig. 4a) suggest that the primary reaction is that of calcite dissolution, of the general form:

$$(1)\quad CaCO_3(s) + H_2CO_3^* = Ca^{2+} + 2HCO_3^-$$

(Stumm and Morgan, 1981)

where

$$(2)\quad CO_2 + H_2O = H_2CO_3^*$$

Although calcite is certainly not the dominant mineral in this terrain, its relatively high solubility and rapid rate of dissolution is enough to control the water chemistry. Incongruent dissolution of anorthite could also account for this 1:2 molar relationship, but rocks of this type are not known in this area. Groundwater is consistently in equilibrium with calcite (Table 2), which also suggests calcite dissolution.

Correlations of HCO_3 with other cations in groundwater are not significant; however, concentrations of Na and Mg are present in amounts greater than in precipitation (Table 1) and may suggest some weathering (incongruent dissolution) of silicate minerals, such as that of albite to kaolinite:

(Albite) $NaAlSi_3O_8(s)+H_2CO_3^*+9/2H_2O=Na^+ +HCO_3^- +2H_4SiO_4+1/2Al_2Si_2O_5(OH)_4$ **(Kaolinite)**

(Stumm and Morgan, 1981)

A 1:2 Na to H_4SiO_4 molar ratio is predicted at equilibrium from this equation. The slope of the regression line in Fig.

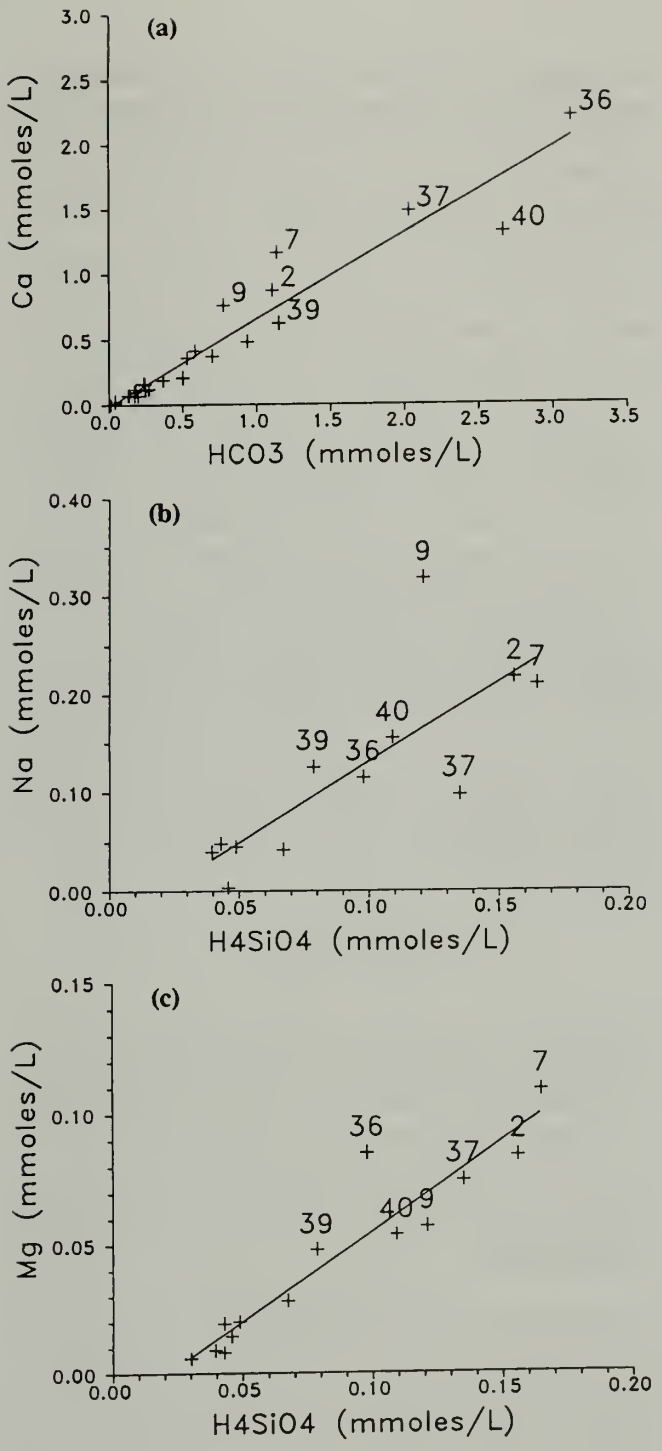

Fig. 4. (a) Plot of Ca and HCO_3 concentrations in mmoles/L. The strong relationship ($r^2 = 0.93$) and nearly 1:2 ($Ca:HCO_3$) molar relationship suggest that calcite dissolution is the predominant reaction; (b) plot of Na and H_4SiO_4 concentrations in mmoles/L. The 2:1 ($Na:H_4SiO_4$) molar relationship suggests albite dissolution, but the weak correlation ($r^2 = 0.70$) suggests incomplete dissolution of Na-silicates; (c) plot of Mg and H_4SiO_4 concentrations in mmoles/L. The correlation ($r^2 = 0.84$) suggests incomplete dissolution of Mg-silicates.

4b is slightly less than 2.0 (1.8), but the correlation is weaker ($r^2 = 0.70$), suggesting that the system is not fully at equilibrium. A similar relationship exists for Mg and H_4SiO_4 (Fig. 4c; $r^2 = 0.84$), and although it suggests some weathering of magnesium silicates, the exact reaction occurring to produce this slope of 0.73:1 is not clear. Data from Reynolds and Johnson (1972) suggest that cations found in glacial meltwater may not be the result of the formation of well-defined, stable clay minerals by incongruent dissolution, but rather the ability of H^+ to exchange rapidly onto clay minerals (Drever 1982). The exchange hypothesis appears reasonable given the short groundwater residence times and high pH values in groundwater.

In contrast to the trend in Ca and HCO_3 ions, the highest concentrations of Mg and Na generally occur near the ice margin (samples 2, 7, and 9; Table 1). These concentrations decrease slightly as Ca (and HCO_3) concentrations increase at downstream groundwater discharge points (Figs. 1, 4(b) and 4(c); Table 1). A negative correlation between Na and Ca is suggested in some samples, which might indicate ion exchange (Na for Ca) in the recently deposited sediment near the ice margin. A more stable equilibrium relationship with silicate minerals may be established downstream, and residence time may be longer.

Kinetic Control of Reactions

The occurrence of very high pH values (Table 1), low Pco_2 values (Table 2), and very low Ca and HCO_3 in all waters adjacent to the ice margin (Table 1) suggest closed system calcite dissolution. Although CO_2 should be abundant in cold, turbulent waters associated with melting ice, pH will generally exceed 8.0 if H^+ from H_2CO_3* is limited or consumed (Freeze and Cherry 1979). Three factors may be responsible for a closed system. First, calcite dissolution is faster kinetically than the dissolution reactions of CO_2 (see equation 2) and subsequent dissociation reactions. Consumption of H^+ by calcite dissolution drives reaction (1) to the right faster than H^+ can be produced and dissociated in (2) (Raiswell and Thomas 1984). Second, H^+ can be exchanged on surfaces of clays, very quickly releasing cations before any actual weathering dissolution of the silicate mineral occurs (Lemmens and Roger 1978; Drever 1982). Finally, the major sources of H^+ replenishment, namely vegetation and organic acids, are absent from this environment. The ultimate effect of vegetation and CO_2 input on calcite dissolution is seen by the general decrease in pH and increase in log Pco_2, Ca and HCO_3 concentrations in downstream groundwater samples (Fig. 1; Tables 1 and 2).

Sulfide Oxidation

Oxidation of soil sulfide minerals and release of sulfate to groundwater are common processes in midwestern glacial sediments and have also been documented in modern temperate glacial environments (Reynolds and Johnson 1972; Raiswell and Thomas 1984). The general reaction is:

(Pyrite) $FeS_2(s) + 3.75\ O_2(g) + 3.5\ H_2O(1) =$
(Amorphous) $Fe(OH)_3 + 2SO_4^{2-}(aq) + 4H^+(aq)$

Subsequent reaction with calcite yields:

$$4H^+ + 2CaCO_3(s) = 2Ca^{2+}(aq) + H_2CO_3(aq)$$

Sulfate concentrations of 245 μg/g derived from total sulfur concentrations of 1277 μg/g are present in till in the vicinity of samples 2, 7 and 9, so pyrite and other sulfide minerals are being oxidized and are important in the early weathering process. However, no strong relationship exists between SO_4 and H^+ or SO_4 and HCO_3. A decrease in pH and a molar relationship of 1:1 between Ca and HCO_3 might be expected if this were a major reaction in the system. Values of pH greater than 8.0 and a 1:2 molar relationship of Ca and HCO_3 suggest that H^+ generated in this reaction is either being exchanged on clay minerals or buffered by the carbonate in the system.

Groundwater apparently changes from a calcium sulfate to a calcium bicarbonate water near Wachusett Inlet (Figs. 2 and 3). Although this presumably reflects the large increase in HCO_3 ions due to CO_2 input from vegetation, there is an actual decrease in sulfate concentrations from a high value of 0.88 mmoles/L to a low value of 0.20 mmoles/L (Table 1). This may suggest variability in the sulfur content of the till, a change in the rate of sulfate production over time, or sulfate removal, perhaps by vegetation and groundwater, from the till.

Summary

The major ion geochemistry of groundwater flow systems developed near the margin of the Burroughs Glacier since deglaciation is dominated by calcite dissolution and carbonate equilibria. Although glacial till is dominated by igneous and metamorphic lithologies, residence times less than five years appear to favor calcite dissolution over silicate mineral weathering. Because of the rapidity of the calcite dissolution, these reactions appear to occur under closed system conditions. Some silicate minerals, such as albite, appear to be from weathering but do not appear to have reached equilibrium conditions. Hydrogen ions (H^+), the driving force behind weathering and dissolution, are in short supply because of the lack of vegetation on recently deglaciated surfaces and because of preferential exchange of H^+ on clay minerals. Hydrogen ions derived from sulfide oxidation do not appear to contribute substantially to the acidity of the system.

The establishment of vegetation on recently deglaciated surfaces and the subsequent release of CO_2 to the soil zone and to groundwater are probably the most important early controls on groundwater geochemistry and result in increased calcite dissolution, subsequent increases in Ca and HCO_3 concentrations, and equilibrium with calcite. Unfortunately, because we could not investigate the chemical evolution of groundwater along a single flow path, the effect of groundwater residence time could not be separated from the effect of CO_2 input in shallow groundwater flow systems. Groundwater changes chemically from a calcium sulfate water to a calcium bicarbonate water away from the ice margin and where flow paths are probably longer. The change is manifested by an increase in Ca and HCO_3 concentrations and an actual decrease in SO_4 concentration. This trend suggests that sulfur content of the till varies, that there is a change in the rate of sulfate production over time (perhaps a residence time effect), or that the sulfate is being removed from the till, perhaps by groundwater or vegetation.

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The Malaspina Glacier Radar Study – A SLAR Investigation of Glacial and Periglacial Features

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Abstract

Side-Looking Airborne Radar imagery of Malaspina Glacier, acquired in 1986, shows anomalous patterns of light and dark radar backscatter that resemble terrain features. After analysis of these data and other remotely sensed data and ground-truth field data, the investigators have concluded that these patterns represent surface expressions of subglacier geomorphology. Further, preliminary analyses indicate that airborne and satellite radar data may be significant tools for glacial studies including mapping selected surface and subsurface features and monitoring some types of glacier processes.

KEY WORDS: Glacier, radar, remote sensing, SLAR, periglacial, image processing, bedrock topography, Malaspina Glacier.

Examination of recent X-band (3.2-cm wavelength) Side-Looking Airborne Radar (SLAR) images of Malaspina Glacier, located in Wrangell-St. Elias National Park and Preserve in southeastern Alaska, reveals a complex pattern of light and dark backscatter responses (Fig. 1) that resemble features in the nearby mountainous terrain (Molnia 1988). Inspection of 1976 and 1980 X-band airborne and 1978 L-band (23.5 cm) Seasat satellite radar data, as well as other data sets, shows that certain backscatter patterns appear to have been stationary for more than 10 years. These stationary patterns are significant because the glacier's surface is actually very dynamic. For example: (1) velocity vectors as great as 300 m/year (Krimmel and Meier 1975) near the center of the glacier, and more than 5 km/year during the 1986-87 surge near the edge of the glacier, have been measured using moraine patterns seen on consecutive Landsat data, and (2) yearly snowfall accumulation and ablation of as great as 5-10 m/year (Krimmel, pers. comm.) have been estimated.

Some aerial photographs and Landsat images of Malaspina Glacier, obtained since 1973, show surface patterns similar to those described above, but they are usually obscured by the annual snow cover in winter scenes and the moraine patterns when the snow is not present. Interpretation of remotely sensed data sets indicates that the analyzed passive sensors

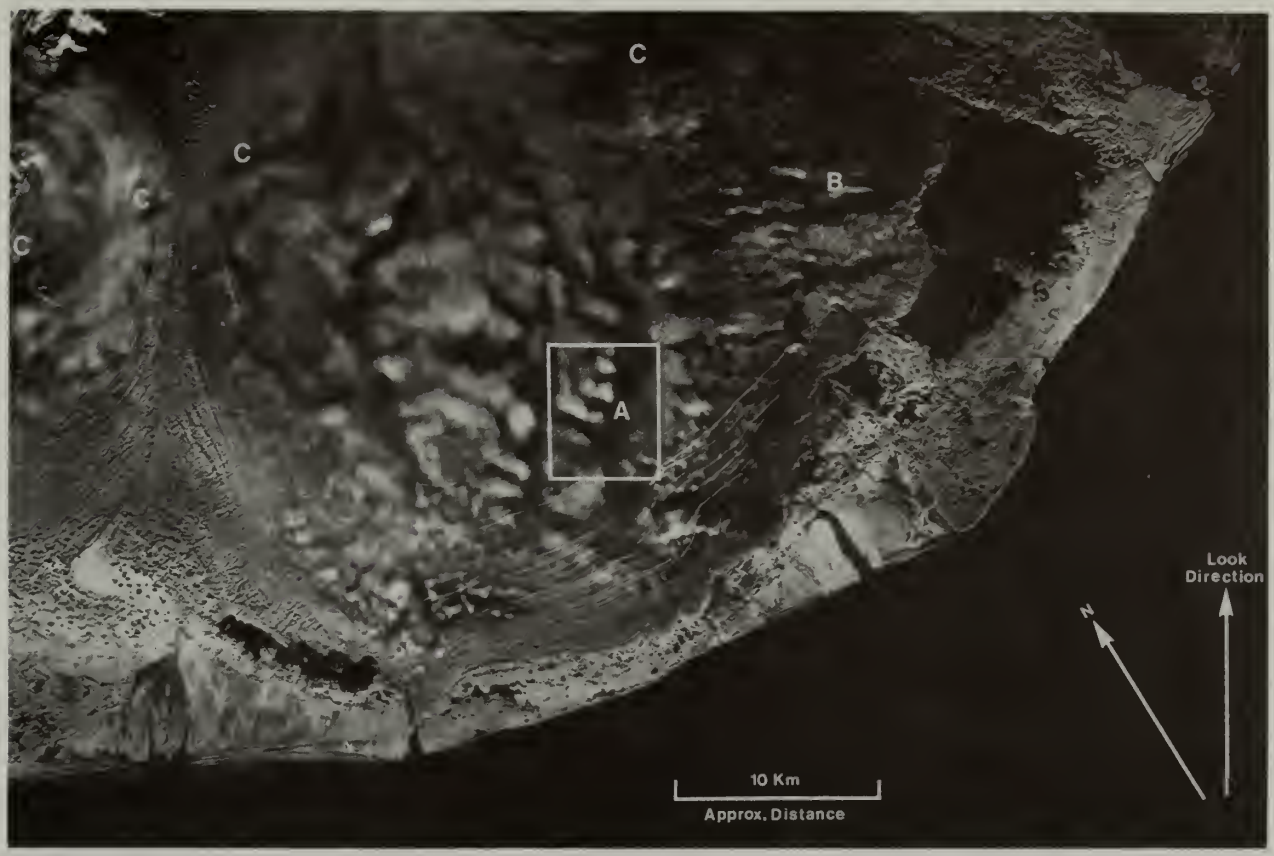

Fig. 1. Side-Looking Airborne Radar image of the lower two-thirds of Malaspina Glacier. The long narrow arcuate lines are moraines. The light and dark, irregular to rounded patterns represent topography highs and lows on the glacier's surface. The three types of surface patterns resemble glacially eroded valleys (A), dendritic morphology (B), and the surface expression of a fault (C). This X-band image was acquired on November 25, 1986, with a look direction of N. 30° E. The depression angle (the angle of microwave illumination below the horizontal) range across the image is from 9° in the southwest to 30° in the northeast. The area contained in the rectangle is shown in Figure 2.

(only receiving emitted or reflected radiation, e.g., aerial photography and Landsat images) do not show the patterns as well as the data from the analyzed active sensors (those that transmit and receive the backscattered radiation, e.g., airborne and satellite radar).

Field Investigations

In September 1988, the U.S. Geological Survey sent an interdisciplinary team (two cartographers, a geologist, a hydrologist, and a physical scientist) to Malaspina Glacier to gather field data in support of this study. The optimum time for visiting the glacier is generally August through October when the glacier's ice surface is exposed following the summer ablation period.

The primary goals of this reconnaissance trip were to: (1) visit the areas on the glacier's surface that correspond to the light and dark backscatter patterns seen on the radar imagery to identify and document the surface conditions that contribute to the patterns, and (2) conduct planetable/alidade transects across selected areas of the glacier's surface to establish the relationship between surface relief and radar backscatter patterns.

Glacial Features and SLAR Interpretation

Three general types of features can be identified from the light and dark backscatter patterns seen on the radar image. These are north-south trending features resembling glacier eroded valleys (Fig. 1, A), east-west trending features with dendritic morphology (Fig. 1, B), and a long, narrow curvilinear feature resembling the surface expression of a fault (Fig. 1, C).

Favorable weather conditions permitted the investigators to spend parts of 6 days on the glacier. All three types of features were visited and 10 planetable/alidade profiles were

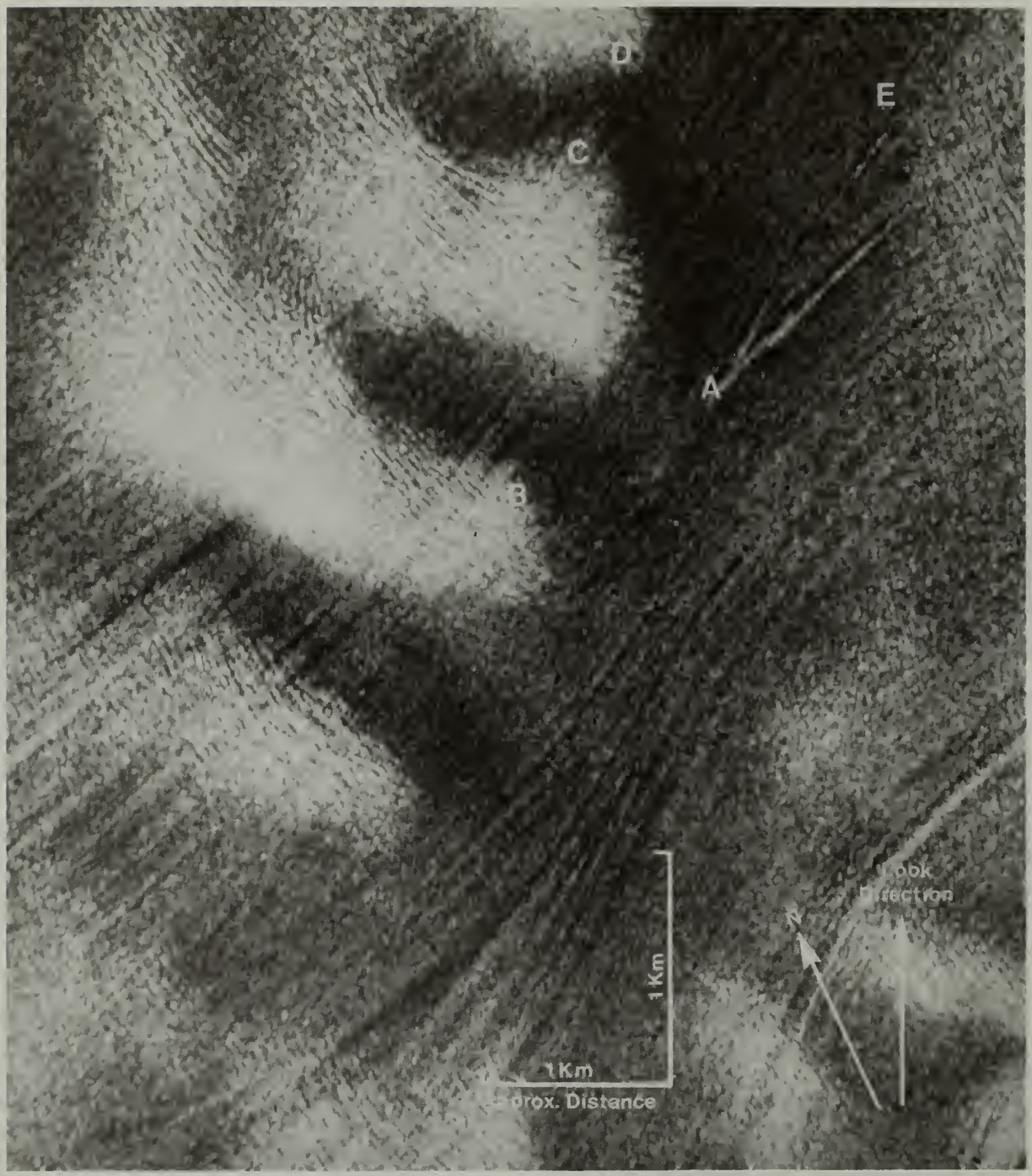

Fig. 2. An enlargement of the area outlined in the rectangle in Figure 1. The tip of the moraine (A) was the base station for a doppler geoceiver and served as the starting point for four planetable/alidade profiles across (A to B, C, and D) and along (A to E) the northeast trending swale. This swale, seen as a dark area on the image because of low radar backscatter, had a relief of more than 40 m. The four dark, elliptical, cirque-like patterns on the left flank of the swale are bounded by bright-return topographic highs. The swales are zones with few crevasses, while the highs are characterized by an extensive crevasse network. The scales parallel and perpendicular to the look direction are different due to SLAR imaging anomalies.

Fig. 3. Oblique aerial photograph taken from approximately 300 m above the surface, looking north across the moraine labeled (A) toward the highly crevassed topographic high (C) on Fig. 2. The tallest mountain on the skyline (5,500 meters) is Mount St. Elias.

Fig. 4. Photograph looking northeast along the swale profile (A to E on Fig. 2). The northern arm of the moraine (A in Fig. 2) is the debris-covered ridge on the right horizon. Most swale surfaces are characterized by a slight hummocky relief, running water, small ponds, and a thin, discontinuous veneer of sediment.

Fig. 5. Photograph looking eastward toward the apex of the moraine (A in Fig. 2). The view is from the beginning of the transition zone between the swale and the topographic high (looking from near B toward A on Fig. 2).

Fig. 6. Photograph looking approximately east up the slope of a topographic high located near the second (C) from the west shown in Fig. 1. The direction of glacier flow is toward the observer. A rectilinear pattern of crevasses is present on many of the slopes of the topographic highs.

surveyed. Surface conditions that could affect radar backscatter were identified and photographed at each site. In addition, a doppler geoceiver base station was established on the glacier to measure latitude, longitude, and elevation. Figure 2 shows the location of the geoceiver station and some of the profiles. Figure 3 shows swales (topographic lows) and topographic highs, corresponding respectively to the dark and light radar backscatter patterns shown on Figure 2.

In general, surface conditions at locations corresponding to the three types of features were similar. Dark areas on the radar image correspond to gentle swales with a maximum relief of up to 40 m. The swales are assumed to be areas of glacial compressional flow, while the topographic highs are considered to be areas of extensional flow; the lack of crevassing in the swales and the extensive crevassing on the highs as seen in both Figures 2 and 3 support this assumption.

The swales contain small streams, pools of standing water, very few crevasses, and a thin, unevenly distributed veneer of sediment. The bottoms of the swales frequently have a low hummocky relief as great as 20 cm (see Fig. 4), with a microrelief as great as 5 cm composed of the above-surface portion of eroded ice crystals.

The transition zone between swales and topographic highs frequently has a moderate to high hummocky relief as great as 1 m (Fig. 5). This zone, as well as the highs, sometimes has a microrelief composed of the surface expression of eroded ice crystals as high as 10 cm. Figure 6 shows a rectangular crevasse pattern (1 to 2 m across) of an area near the top of a moderate topographic high. Many of the highs have crevasses greater than 5 m across. In addition, the highs frequently have a discontinuous cover of angular rock fragments.

Krimmel and Meier (1975) analyzed enhanced Landsat images of Malaspina Glacier and noted "subtle tonal variations" corresponding to some of the features identified on the radar imagery. These investigators stated that the tonal variations "may be a reflection of the basal features, and perhaps can be interpreted as subglacier stream beds or differential erosion of geologic structures or formations" and "may relate to bedrock roughness elements and hence subtly reflect the subglacier topographic relief." The field data gathered in September 1988 and the analysis of historical airborne and satellite radar data (1976, 1978, 1980, and 1986) support the belief that there is a strong relationship between surface swales and subsurface basal features. Further, with negative relief up to 40 m, the features on the surface of the Malaspina Glacier seem to mimic subsurface troughs, cirques, and stream channels (Molnia 1988). This curvilinear feature may correspond to the trace of one of the boundary faults separating the North American Plate and the Pacific Plate.

On the basis of preliminary field data and analysis of SLAR and other data, we have developed a working hypothesis, outlined the research objectives and methodology, and defined the goal and applications for the next phase of this study.

Future Working Hypothesis

The mottled light and dark patterns seen on radar imagery (Fig. 1) correspond to topographic expressions of the glacier's surface. The light areas on the image (areas of high radar backscatter) are topographic highs while the dark areas (areas of low radar backscatter) are topographic lows or swales with up to 40 m of relief. Further, the surface topography of the glacier is thought to be a subdued expression of subglacial features and topography at depths as great as 600 m below the ice surface (Molnia 1988).

We conclude that there is greater radar backscatter from the topographic highs than from the lows because of two mechanisms: (1) the large crevasses and hummocky terrain that characterize the highs act as radar reflectors while the lows have fewer crevasses and a flatter surface, and (2) the radar signal is reflected away from the sensor by standing water and flowing streams that characterize the topographic lows during the fall of the year, and the radar backscatter is generally reduced when the lows are snow-covered due to the complicated volume scattering, energy loss, and surface-scattering relationships. In addition, a thin, unevenly distributed veneer of sediment is usually covering the surface in the lows while the highs frequently have some rocks distributed on the surface. The effect of these materials, as well as the contribution of other parameters such as slope, aspect, ice crystal size, and snow phase, is not as yet well understood.

Research Objectives and Methodology

The research objectives of the Malaspina Glacier Radar Study include: (1) defining the relative contribution of the parameters (ice depth, flow rate, crevassing, snow scattering and energy loss, surface sediment, slope, aspect, etc.) that control the radar backscatter returns seen on Malaspina Glacier; (2) identifying the glacial and periglacial features that can be effectively mapped using radar; and (3) identifying the glacial processes that can be monitored using radar.

Grand Plateau Glacier, located in Glacier Bay National Park and Preserve approximately 150 km southeast of Malaspina Glacier, may also be used as a control site for the study of some of these parameters. Most of the remotely sensed data of Malaspina Glacier also cover Grand Plateau Glacier. This glacier is accessible and is a good site for gathering field data.

The methodologies to be used to achieve the objectives of this study are: (1) collect field data for identifying features and

processes observed on remotely sensed data; (2) digital processing techniques to geometrically correct, enhance, and analyze the many remotely sensed and other data sets; and (3) merge the digitally processed data using geographic information systems to allow other researchers access to the data for continued analysis.

Long-term Goal and Applications

The principal long-term goal is to develop improved and cost-effective remote sensing techniques for mapping glacial and periglacial features and monitoring glacial processes in polar and subpolar areas. This study will emphasize radar and microwave sensors.

Airborne techniques that are transferable to satellite technology will be stressed. This emphasis is appropriate because within the next decade more than 10 radar and microwave satellites will be launched by the United States, Canada, Japan, the European Space Agency, and others.

The applications of this study that are currently being investigated include improved planimetric mapping of glacier surfaces and transition zones, monitoring of glacier movement, and measurement of snow accumulation and ablation. In addition, two other possible applications of remote sensing radar for some glaciers and ice-covered areas are identifying zones where potential landing sites and ground transportation are possible because the swales appear to be zones with few crevasses, and improving estimates of ice volume because the radar backscatter patterns of the glacier's surface are thought to represent an expression of subglacial topography. This latter potential application may have significant importance for global change investigations by developing improved estimates of the volume of ice contained in ice sheets and glaciers worldwide.

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Channel-forming Processes Active in Queen Inlet, Glacier Bay, Alaska

by

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Abstract

Queen Inlet, a marine-outwash fjord, is the only Glacier Bay fjord in which an extensive channel system is cut into the Holocene sediment fill of the fjord floor. Four channels, beginning at the base of the prodelta slope, have merged into one main channel midway down the fjord. The channel that extends the length of the fjord has cut deeply into the scarp that separates this hanging tributary fjord from West Arm. The Queen Inlet channel ends on the floor of West Arm as several small distributaries that form part of a lobate deposit. Sand from the inlet channel and the fan-like lobate deposit (in contrast to the mud from the fjord floor), together with the steep truncated walls of the channels, point to turbidity currents generated from submarine slides of oversteepened prodelta sediment as most likely to have created this apparently active channel system. Queen Inlet and other fjords throughout the world that contain channels are all marine-outwash fjords. Perhaps the tidewater glacial fjords do not have sufficient initial gradient as well as reservoir of potentially unstable sediment to generate channel-cutting turbidity currents.

KEY WORDS: Channels, turbidity currents, marine-outwash fjords, submarine slides, retreating glacier.

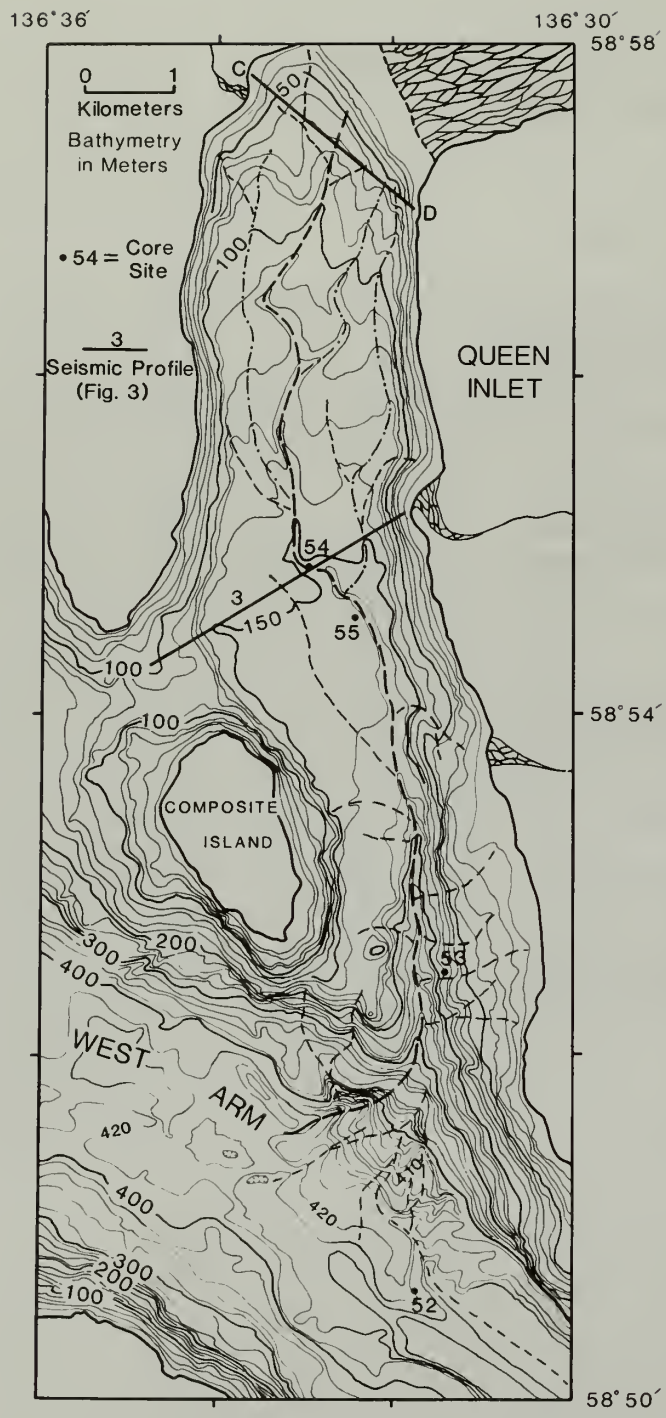

Fig. 1. Bathymetry of Queen Inlet, Glacier Bay, with channel thalwegs superimposed (main channel: thick dashed line; three smaller channels: thin dash-dot lines; smaller tributaries: thin dashed lines). Contour intervals: slopes, 20 m; fjord floor, 10 m; lobate fan area below Queen Inlet, 2 m. Datum is mean lower water. (Bathymetric soundings by U.S. National Oceanic and Atmospheric Administration, 1970). Numbered dots are sample locations. C-D is line of comparison profiles—NOAA, 1970 vs. USGS, 1984.

Queen Inlet, a marine-outwash fjord that enters the West Arm of Glacier Bay as a hanging valley (Fig. 1), was occupied by Carroll Glacier prior to 1860-79 (Muir 1895). Since that time, this glacier, the source of a melt-water stream with a heavy load of sediment, has retreated about 3 km from the head of the fjord and has built a 6-km² delta outwash plain. The floor of Queen Inlet is incised by a dendritic channel system (Fig. 1), in contrast to floors of other Glacier Bay fjords none of which have large incised channel systems. Similar channel systems have been reported from other marine-outwash fjords. (Syvitski et al. 1987). The purpose of this paper is to describe the fjord floor channels of Queen Inlet and speculate about processes responsible for the development of these channels.

Data Collection

We contoured the bathymetry of Queen Inlet from soundings collected by the U.S. National Oceanic and Atmospheric Administration (NOAA) in 1977 (smooth sheets H9138 and H9141, scale 1:20,000). These soundings in fathoms were tidally corrected and corrected for seawater characteristics. We converted the soundings to meters and contoured to a 10-m interval on the fjord floor, a 20-m interval on the fjord walls, and a 2-m interval on the floor of the West Arm (Fig. 1). We collected high-resolution seismic-reflection profiles and two single-channel 20-J sparker profiles in the inlet during the period 1978-84 from U.S. Geological Survey (USGS) research vessels *Growler* (1978) and *Sea Sounder* (1978) and the U.S. National Park Service merchant vessel *Nunatak* (1980; 1984). Navigational control was by radar and visual shoreline sightings. Bottom samples were collected with gravity corer and grab samples on two 1979 cruises, the USGS research vessel *Sea Sounder* and the NOAA ship, *Surveyor.*

Geomorphology of Queen Inlet

Queen Inlet, shorter than many of the Glacier Bay inlets, is about 12.5 km long and 2.7 km wide at the shoreline. The floor of the fjord narrows from 2 km in width to 1.2 km wide near its mouth. The height of the submerged walls of Queen Inlet averages about 100 m in the upper part and 165 m in the lower part of the inlet, gradients averaging about 16°. The overall gradient of the fjord floor from the prodelta to West Arm is about 1° and ranges from 5.5° on the prodelta to about 0.5° opposite Composite Island. Queen Inlet enters West Arm as a hanging valley (Fig. 1), down a steep (13-18° gradient) erosional scarp that was probably cut by a large trunk glacier (Goldthwait 1963). A low-relief fan-shaped mound at the base

Table 1. Dimensions of Queen Inlet channels.

Name	Length (km)	Gradient (deg)	Width (m)[3]	Relief (m)	No.[4]
Main[1]	12.5	1.6	354 (138)	30	18
Main[2]	10.5	0.6	273 (133)	20	16
East	2.6	1.3	163	13.6	5
West	2.2	4.2	175	5.2	5
Base east wall	4.5	1.3	144	5	9

[1]Entire channel: prodelta to base of scarp in West Arm.
[2]Main channel to top of scarp in West Arm.
[3]Width measured at top of channel banks, except for main channel where width was also measured across floor of channel, in parentheses.
[4]Number of seismic-profile crossings.

of the scarp (Fig. 1) has formed below the deep main channel emerging from Queen Inlet. The gradient of this incised channel is about 7°. Several small apparently distributary channels extend from the irregular lumpy fan-like morphology near the scarp onto the distal region of West Arm (Fig. 1). The floor of Queen Inlet is incised by a sinuous channel system that is dendritic in the upper part but becomes more trellised in the lower part of the inlet (Fig. 1). The main channel has a gradient of 5° down the prodelta front and varies from 2.9° in the upper fjord to 0.2° at a distance of 7 km down the fjord. Other dimensions of the main channel are given in Table 1. Three smaller channels and several smaller tributaries are incised into the floor of Queen Inlet (Fig. 1). The channels vary from deep and V-shaped where the main channel cuts into the scarp to less relief and U-shaped in the upper part of the fjord.

Historical Deglaciation

Carroll Glacier retreated to the head of the present fjord in the late 1800s to form Queen Inlet. The terminus was tidal about 1911, when it began to recede and concomitantly build a delta into the fjord from the ice cliff (Field 1964). The glacier advanced again about 1919, redistributing old deltaic outwash into deeper water, but had retreated and by 1924 no longer reached tidewater. It is presently about 3 km above tidewater. Field (1964) suggests that the building of a delta outwash plain was more responsible for isolating the glacier front from tidewater than was the retreat. Shoaling has occurred rapidly at the head of Queen Inlet since the 1919 advance. Bathymetric soundings by NOAA in 1970 across the front of the delta (Fig. 1, line C-D) indicated a maximum depth of 70 m, whereas our soundings in 1984 measured depths to 40m, suggesting a rate of sediment accumulation on the prodelta as much as 2.1 m/year.

Sediment Distribution

The suspended sediment load at the delta front of Queen Inlet was in excess of 1 g/L during September—the time of maximum stream discharge (Hoskin and Burrell 1972). This high concentration can be seen as a well-defined sediment plume that extends from the braided channel mouths of the main delta. Sediment samples yielded particle-size modes of fine sand to coarse silt for 12 channel samples and fine silt for 8 fjord-floor samples (Hoskin and Burrell 1972). Two gravity cores (54 and 55) obtained from the main channel in Queen Inlet (Fig. 1) consisted of mud, laminated sandy to silty mud (60 to 70% silt), and sand (Figs. 1 and 2). Lower in these cores, laminae became more numerous, thicker, and contained graded sand (48 to 53% sand) lenses as much as 2 cm thick. These, together with sharp lower boundaries,

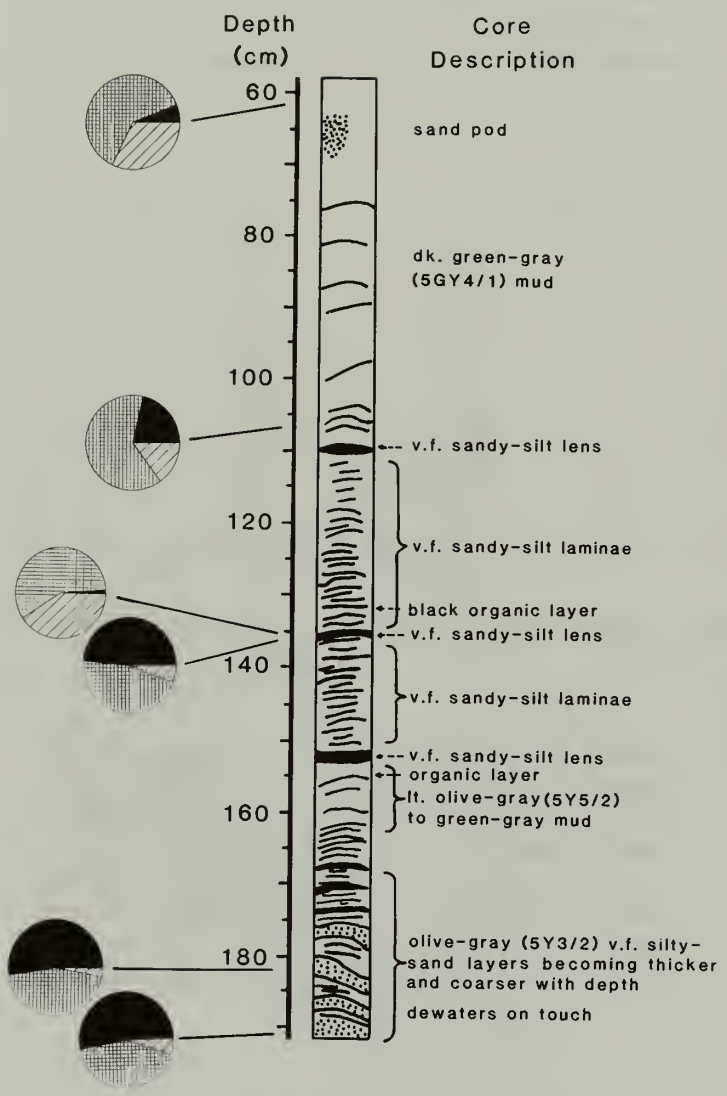

Fig. 2. Sketch of gravity core 54 collected from main channel in Queen Inlet at water depth of 150 m, and pie charts for subsamples showing percentages of sand (black), silt (squares), and clay (slanted lines). See Fig. 1 for location of core.

suggest turbidity current deposits (Fig. 2). Other layers varied from fine sand to coarse silt 2 to 3 mm thick to thin silt laminae less than 1 mm thick. These layers are similar to those in nearby Muir Inlet (Mackiewicz et al. 1984) and also to those in very old glacial marine sections in the Precambrian Gowganda Formation in southern Ontario, Canada (Miall 1985). One short (25 cm) core (53) from the steep east wall, where the main channel cuts the morainal bank at the mouth of Queen Inlet in 230 m of water (Fig. 1), contained an average of 80% gravel (to 100 mm in diameter), 12% sand, and 8% mud. A core (52) in 428 m of water in West Arm below Queen Inlet (Fig. 1) consisted only of a core-catcher sample of muddy sand (90% fine to very fine sand). The presence of shallow-water benthic foraminifers *(Elphidium clavatum)* indicates down-slope displacement of the sand. Two other sampling attempts in West Arm, northwest and southeast of the mouth of Queen Inlet, yielded small amounts of dark gray fine sand overlain by a thin layer of watery olive-gray mud suggesting the presence of a layer of fine sand along the floor of West Arm near Queen Inlet. This sand also contained displaced shallow-water benthic foraminifers *(Elphidium clavatum* and *Elphidium* spp.).

Two mechanisms could account for accumulation of sand layers and silt laminae in the fjord fill and sandy silt on the channel floors, namely: (1) the incoming sediment-laden voluminous melt-water stream separates at the delta front, the suspended material enters the inlet in an overflow plume, and the bedload portion continues down the delta front and out across the fjord, cutting and maintaining channels and depositing the bedload of sandy silt and silty sand within the channel; or (2) the bedload accumulates rapidly on the submarine delta foreslope with accompanying buildup of pore-water pressure leading to an underconsolidated state and resulting instability. This sediment may eventually fail due to oversteepening, tidal drawdown (Karlsrud and Edgers 1982) or to some kind of repeated agitation, whether shaking from earthquakes (Syvitski et al. 1987) or wave action generated by upfjord winds (Prior et al. 1987). The resulting mass movement, whether a slide or slump, may become transformed eventually into a sediment gravity flow, as described by Middleton and Hampton (1976). Such a flow may travel the length of the fjord and down into West Arm or, depending on its momentum, may stop somewhere along the Queen Inlet channels. Evidence for recent channelized turbidity currents has been reported for two marine outwash fjords in British Columbia. Prior et al. (1987) related turbidity current generation to a heavy runoff flood from snow melt in May 1986 in Bute Inlet. Their instruments indicated flows moving as much as 335 cm/sec with thicknesses of more than 30 m; sediment up to coarse sand size was collected in traps 6 or 7 m above the bottom. Hay et al. (1983) reported that surge and continuous turbidity currents transported the sediment that makes up the coarse-grained turbidite layers and the intervening muds cored in Rupert Inlet, but they suggest that surge-type flows are the primary erosive agents responsible for cutting and maintaining the channels.

Acoustic Profiles

Seismic-reflection characteristics of Queen Inlet change from disrupted discontinuous reflections underlying the steep irregular prodelta slope to relatively flat-lying continuous sub-

bottom reflections beneath the low gradient mid-fjord area to the disrupted, disorganized reflections at the steep scarp that marks the mouth of the inlet. A prominent morainal mound or ridge at the mouth of the fjord is capped by a 20-m-thick layer of sedimentary strata; the ridge is cut by a deep channel near the fjord mouth. The erosional nature of the channels incised in sediment that has accumulated on the floor of the inlet is clearly shown by the abruptly terminated reflections visible on acoustic profiles (Fig. 3). Pronounced terraces (5 to 10 m in relief, 100 to 200 m in apparent width) have been carved on the sides of the channels. Figure 3 illustrates a mid-fjord profile with a 100-m-wide terrace about 8 m above the channel floor on the northeast wall, and a 20- to 30-m-wide terrace on the opposite wall of the channel. Most profiles show hummocky disrupted sediment at the base of the channel walls (Fig. 3). These sediment masses have the appearance of large slides or slumps. Disrupted, broken, and irregular reflections within the fjord fill (Fig. 3) also indicate that episodes of mass movement contributed to the sediment that has accumulated in the inlet, perhaps since the last retreat of Carroll Glacier more than 100 years ago. The total sediment fill varies in thickness from 10 to 12 m at the upper end to 140 m in the middle part of the fjord. The recent fill in Queen Inlet consists of two units separated by an intense continuous reflection (Q, Fig. 3). The lower unit may consist mostly of muddy sediment (Fig. 3, unit 2), whereas the upper unit consists of interspersed fine mud and coarser silt-to-sand layers or laminae. This change in sediment may have occurred when the inlet evolved from a tidewater-glacial to a marine-outwash fjord. Filled channels are present on some profiles, but only in the upper part of the sediment (to a depth of 10 to 15 m), suggesting that the channels have been developing in much the same location throughout their existence.

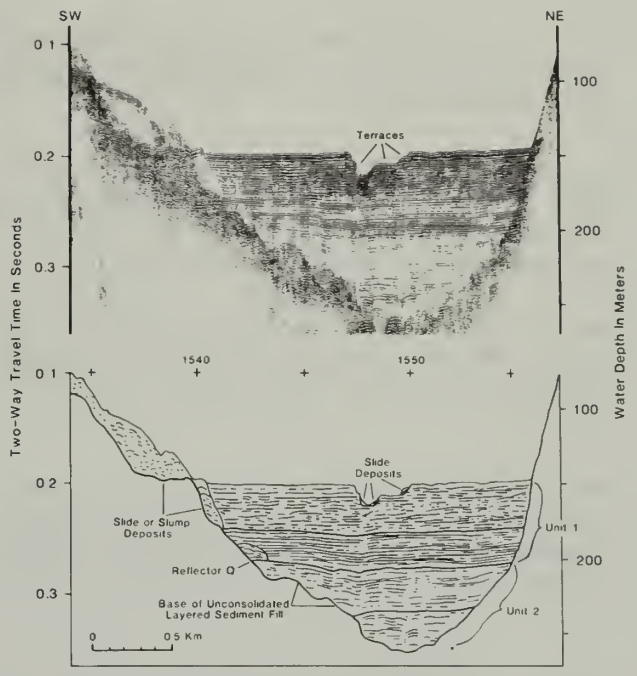

Fig. 3. Minisparker (500 J) profile and interpretive sketch from Queen Inlet showing terraces bordering main channel in mid-fjord. Vertical exaggeration, x 9.3. See Fig. 1 for location of profile.

Summary and Conclusions

The channel system cut into the floor of Queen Inlet was probably formed by surge-type turbidity currents that originated from the relatively steep face of the Carroll Glacier outwash delta. The lack of buried channels in the lower unit of the fjord sediment fill indicates the recent origin of the channels, perhaps in the last 40 to 50 years as the outwash delta developed. Although unique to Queen Inlet in Glacier Bay, channels have been found incised in the floors of other high-latitude fjords. Extensive channel systems appear to be limited to marine-outwash fjords with well-developed delta systems. Apparently, tidewater glaciers do not store enough sediment on a steep enough slope to create large surge-type turbidity currents. The most probable scenario to explain the channel system begins with submarine slides that develop on the relatively steep ($>5^0$) delta front due to the failure of overpressured and oversteepened sediment. The slides become transformed into turbidity currents that surge down the low gradient ($< 1^0$) of the fjord floor. In spite of the low gradient, sand and even coarser sediment can be transported the length of the fjord valley and down the prominent scarp at the mouth of the fjord into the adjacent West Arm of Glacier Bay where sandy fan-like lobes are forming. The sharply truncated reflections of the fjord fill along the walls of the Queen Inlet channel system and the sandy sediment recovered from the channel floors indicate continuing turbidity-current activity.

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Suspended Sediment Dynamics of Glacial Deltas: Implications for Maintenance of Submarine Channels

by

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Abstract

Outwash streams of Riggs and Carroll Glaciers have rapidly built deltas with large intertidal zones in Riggs embayment, Queen Inlet, and Wachusett Inlet. Tidal stage has a dominant effect on fjord sedimentation, with a smaller role played by discharge fluctuations in meltwater streams.

Portions of the deltas are flooded intermittently during high spring tides and continuously during neap tides, backing up sediment-laden meltwater streams and causing deposition of coarse and flocculated fine sediment on the delta plain. Some fine sediment escapes into the fjord in dilute overflow plumes. During low spring tides, the entire delta plain is exposed, allowing meltwater streams to reentrain large quantities of stored sediment from channels, channel banks, and tidal flats. Sediment is then deposited rapidly close to the delta by sediment gravity flows on the delta front and by suspension from highly charged sediment plumes.

We postulate that these low spring tide drawdown effects produce suspended sediment concentrations sufficiently high that inflowing plumes could become more dense than the saline fjord water. The plume would then dive below the surface as an underflow. Such underflows may be active in submarine channels that have been described in Queen Inlet. Water column profiles of salinity, temperature, and suspended sediment concentration during a spring tidal period in July 1988 indicated slightly fresher and more turbid water within one well-defined submarine channel. No current velocity data is available, so it is not known whether these features represent surge currents generated by delta-front slumping or more continuously active underflows. In either case, future monitoring of current velocity and water characteristics within the deep channel will yield interesting insights into the generation and maintenance of these submarine channels.

KEY WORDS: Deltaic sedimentation, tidal effects, suspended sediments, density flows, submarine channels, Queen Inlet.

Upon entering a receiving basin, river water disperses in a distinct plume. In marine waters, high salinities usually overwhelm any density effects of inflow temperature or suspended sediment concentration, and so plumes typically spread over the surface as overflows. In rare instances such as the Yellow River, China (Wright et al. 1988), very high suspended sediment concentrations cause the inflowing plume to dive below the surface and flow along the bottom or along a density gradient within the marine water column. Several workers have suggested that such conditions may also occur in temperate glacial environments such as Glacier Bay, Alaska, where glacial meltwater commonly carries high suspended sediment loads (Powell 1983; Mackiewicz et al. 1984). However, no such underflows have yet been documented. Some observers of the ancient sedimentary record have nevertheless proposed that underflow activity produced some glacimarine sequences (e.g., Domack 1984).

We have been studying delta-forming processes at Riggs Glacier (Muir Inlet) and Carroll Glacier (Queen and Wachusett Inlets) in Glacier Bay since 1985. We have observed that the reentrainment of delta-plain sediment by outwash streams during low spring tides results in increases of stream suspended sediment concentrations by several fold. A logical extension of this mechanism is the potential for production of river plumes dense enough to cause underflows. It thus seems possible that underflows induced by tidal drawdown are responsible for the generation and maintenance of axial submarine channels which have been noted in Queen Inlet (Hoskin and Burrell 1976; Carlson et al. 1989 and this volume).

The Drawdown Mechanism

Glacial meltwater carries large amounts of sediment into Glacier Bay. In front of terrestrially grounded glaciers, much of this sediment is rapidly deposited as deltas with extensive intertidal zones. The elevation of the delta plain edge typically lies slightly below mean lower low water stage. The flood and ebb of the tides through the neap-spring cycle has a dominant effect upon sediment distribution (Smith et al. in press).

During neap tides, a portion of the delta plain remains continuously flooded. This backs up meltwater streams, causing deposition of bedload and some suspended load in stream channels and on mudflats. The remaining suspended sediment is carried into the fjord in a relatively dilute overflow plume. Thus, sediment accumulates on the delta plain continuously for periods of about one week. Ensuing low spring tides expose the entire delta plain, allowing reentrainment of some of the recently stored material. A ready source of easily eroded sediment results in very high stream suspended sediment concentrations, up to an order of magnitude greater than at the glacier portal. Do these concentrations become sufficiently high that plume density exceeds that of the saline basin water, causing underflows?

Suspended Sediment Processes in Queen Inlet

Ideal conditions for testing this hypothesis exist in Queen Inlet. Measurements of the meltwater issuing from Carroll Glacier in July 1988 showed already high sediment concentrations of about 20 g/L. At the low spring-tide stream mouth (at the edge of the delta plain), concentrations ranged from 30-90 g/L. A large portion of this sediment load was sand and thus was rapidly lost from the plume. Nonetheless, the concentration of suspendable particles was high.

Figure 1 shows the bathymetry of Queen Inlet as inferred from acoustic profiles made in July 1988. The submarine channels begin to become defined at 70-80 m depth. Two tributaries join about 2.5 km from the delta edge. At "B," the channel is approximately 120 m wide by 10 m deep (Fig. 2). "A" and "B" mark locations of salinity, temperature, and suspended sediment concentration profiles determined during spring tidal periods in July 1988. Location A is on the delta foresets, above the depth of channel establishment. Location B is in the main channel. Salinity and temperature measurements were made with a Kahlsico conductivity/temperature probe. Sediment concentration was obtained from filtered water samples obtained with a Van Dorn bottle. Data were collected with the able assistance of Jorie Clark, Paul Gottler, Lewis Hunter, and Monica Tsang.

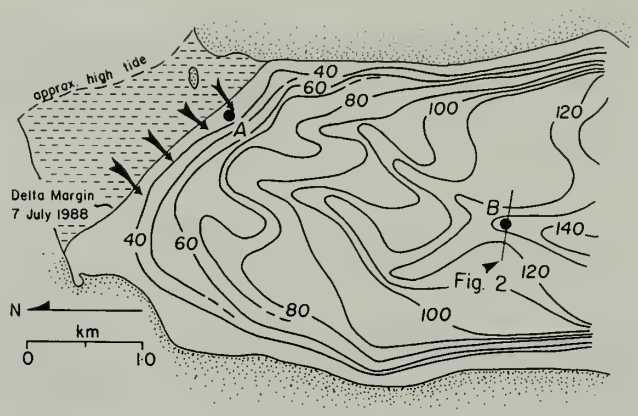

Fig. 1. Queen Inlet bathymetry, 1988. A and B are sampling locations of Fig. 3. Line through B depicts track of Fig. 2.

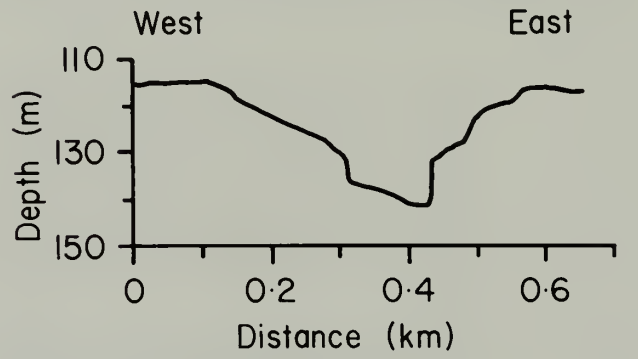

Fig. 2. Line drawing of acoustic profile of axial channel. Vertical exaggeration is 10X. See Fig. 1 for location.

The two profiles show several similar features (Fig. 3). Both exhibit an overflow plume of relatively fresh water with a steep halocline to the deeper marine waters. The plume nearer the delta (Fig. 3A) is colder and has much higher sediment concentrations than the underlying water. At location B, much of the sediment has settled to greater depths (there is a mid-depth maximum of 0.45 g/L at 25 m).

More important for this discussion is the slight freshening and strongly increased turbidity at the base of each water column. In Figure 3A, salinity decreases from a maximum of 29.8 ppt at 12 m to 28.1 ppt at 30 m, a difference of 1.7 ppt. This decreased salinity is apparently balanced by a two-fold increase in sediment concentration from 0.85 g/L (g/L~ppt) at 10 m to 2.63 g/L at 29 m, a difference of 1.8 ppt, as well as a slight decrease in temperature below 24 m.

In profile B (Fig. 3B), salinity decreases by 2.1 ppt between 127 and 136 m. There is an abrupt increase in sediment concentration, from 1.19 g/L at 127 m to 3.50 g/L at 136 m, an increase of 2.3 ppt. No accompanying temperature data are available. Thus, as in profile A, decreased density due to lower salinity is balanced by an increase in suspended sediment concentration. It is interesting that the freshening and increased turbidity in Fig. 3B occur very nearly at the level of the channel banks (~128 m, Fig. 2).

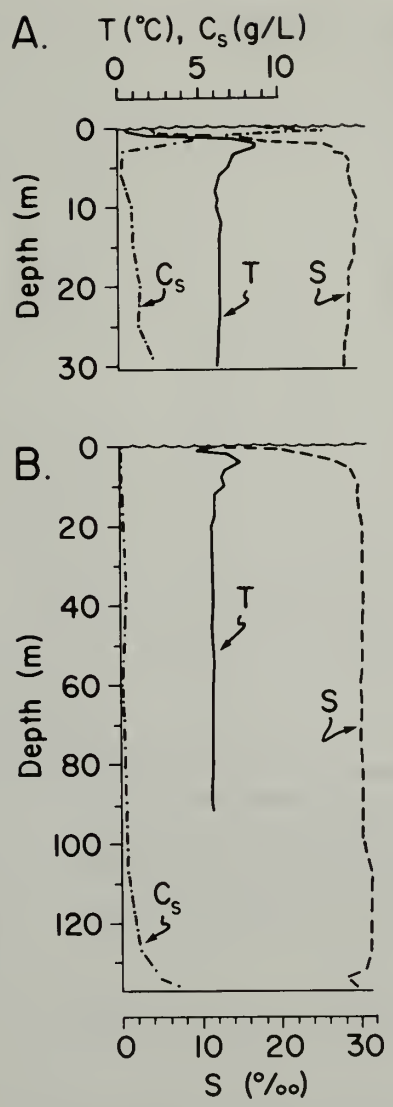

Fig. 3. Water column profiles of salinity (S), temperature (T), and suspended sediment concentration (Cs). Locations A and B are indicated in Fig. 1. Note difference in depth scales between profiles.

Discussion

Does the increased suspended sediment concentration and decreased salinity of these profiles indicate a surge current or a quasi-continuous underflow (c.f. Smith and Ashley 1985)? The profiles are strikingly similar to those of Wright et al. (1988), where underflowing Yellow River water produced an identical salinity drop, though suspended sediment concentrations were two to three times higher. However, fresh water might also be entrained in fluvial bedload avalanching down the foresets and incorporated into sediment gravity flows. The crucial missing data are prolonged current velocity measurements. In similar profiles measured during the same spring tidal periods, bottom currents of up to 20 cm/s were observed (unpublished data). The velocity measurements lasted only a few minutes, however, so the duration of the current could not be determined.

Conclusion

We infer from these data that the submarine channels in Queen Inlet are generated and maintained by turbid density currents (see also Carlson et al. 1989 and this volume). Also, these currents are connected to the influent streams. Further work involving current meter arrays is needed to ascertain whether the currents are surging or quasi-continuous.

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Circulation and Suspended Sediment Dynamics in McBride Inlet, a Tidewater Glacial Fjord

by

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Abstract

A submarine, subglacial stream dominates fjord circulation and sediment dynamics in McBride Inlet during the summer months. Upwelling occurs near McBride Glacier as sediment-laden freshwater rises buoyantly from 100 m depth to the surface. Suspended sediment concentrations near the surface of the upwelling vary with stream discharge but may reach 1.4 g/L. The upwelled water produces a 20-m thick brackish (salinity always >5‰) surface layer that flows downfjord with a maximum velocity of 20 cm/s. The concentration of sediment transported in the surface layer is proportional to the current velocity which is affected by tidal stage and wind. Most sediment is transported in a 4-m thick layer, 4 to 6 m below the surface rather than in a thin plume at the surface.

Tidal forcing produces weak upfjord currents below 40 m depth. Renewal of bottom water occurs from mid-June to August because the density of deep water is less than the incoming tidewater due to mixing with the submarine discharge.

Submarine discharges from tidewater termini can produce favorable conditions for high phytoplankton productivity. Transport of suspended sediment downfjord in a plume beneath the surface does not restrict light to the upper 4 m of the water column. A diatom bloom was observed to extend downfjord from within 0.25 km of the tidewater terminus of Muir Glacier during mid-July 1987.

KEY WORDS: Tidewater glacier, glacial fjord circulation, deep water renewal, suspended sediment, phytoplankton.

Glacier Bay is one of the few locations where interactions between temperate glaciers and the sea can be studied. We have studied fjord circulation and sediment transport near a tidewater terminus in one small inlet in an effort to better understand the sedimentary deposits produced during marine glaciation. This allowed us to gather baseline measurements of salinity, temperature and suspended sediment in order to assess controls on fjord sedimentation in response to tides, seasonality in discharge, glacial retreat and precipitation events (Cowan 1988; Cowan et al. 1988). Data was collected during June–August 1984-1987 and during two weeks in January 1986.

Study Area and Methods

McBride Glacier separated from Muir Glacier in 1946 (map in Powell 1984). From 1966 to 1974, the McBride Glacier terminus maintained a stable position at the inlet entrance,

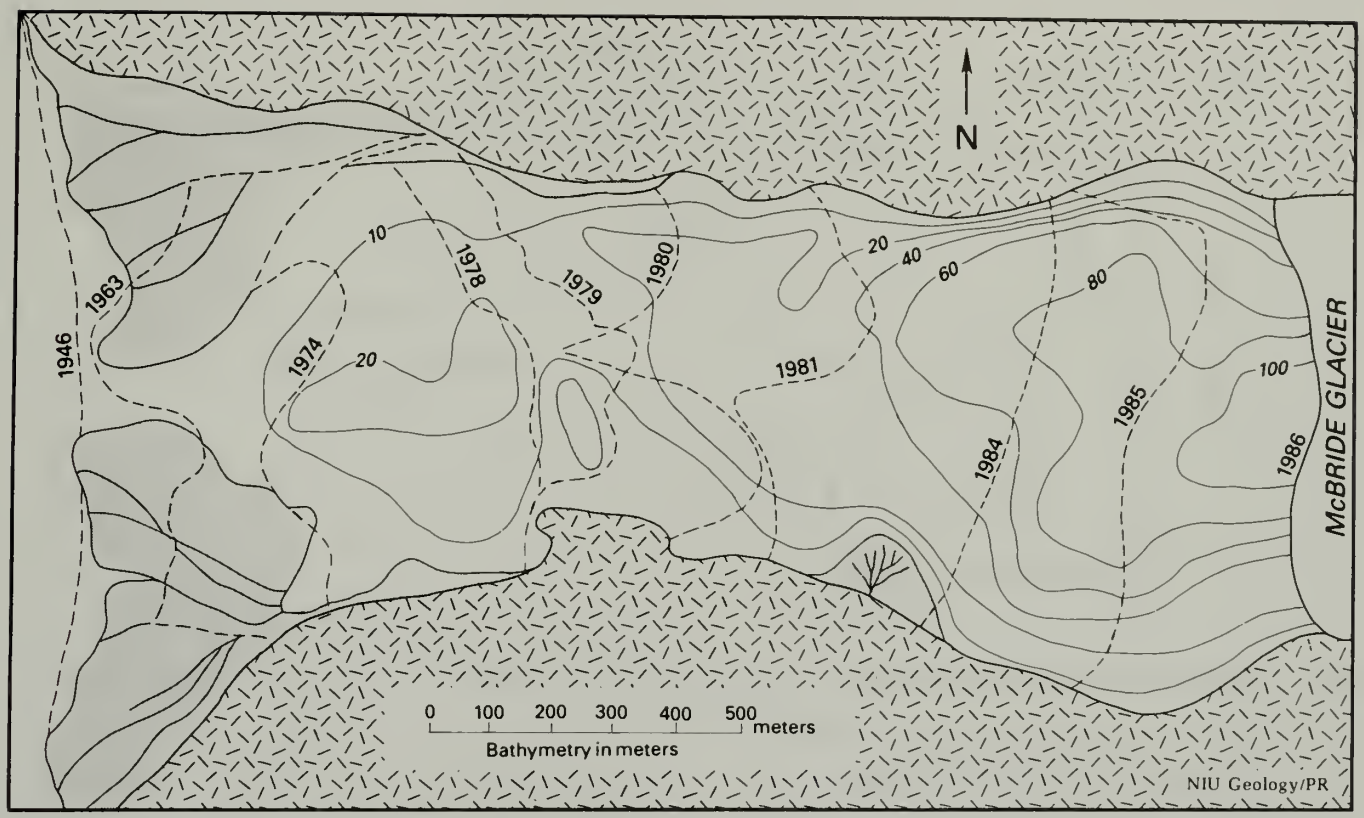

Fig. 1. Map showing position of the McBride Glacier terminus from 1946-1986. Bathymetry is shown for summer 1986. The "island" in the western basin is referred to as the shoal.

and meltwater streams constructed deltas in front of the glacier (Fig. 1). Slow retreat occurred from 1974 to about 1980, and a shallow tidal lagoon formed. More rapid retreat since 1980 has opened up 1.9 km-long McBride Inlet (Fig. 1). Today, McBride Inlet joins Muir Inlet through a narrow channel cut in the old deltas. This channel has remained open because of erosion by stream discharges while in ice-contact and subsequently by tidal currents.

McBride Inlet has two basins. The eastern basin slopes toward the glacier where it reaches a maximum depth of 100 m at the terminus. The gently sloping western basin averages 20 m depth and acts as a broad, shallow sill over which exchange occurs between Muir Inlet and the deep basin. A shoal, exposed at low tide, was built up during the slow retreat between 1978-1980 and is thought to be mainly from subglacial streams (Powell and Molnia 1989; Fig. 1).

During this study, time-series vertical salinity and temperature profiles were collected with a salinometer at anchored stations throughout the inlet. Water samples were collected with a Van Dorn bottle (1- or 3-L volume) to measure variations in suspended sediment concentrations and particle size. Samples were vacuum-filtered on pre-weighed, 0.8 micron membrane filters. Detailed descriptions of field methods and results are outlined by Cowan (1988).

Results

Submarine Discharge

McBride Glacier is drained by one main meltwater stream that discharges from a submarine tunnel into the fjord. The subglacial discharge appears as a turbid upwelling at the water surface near the glacier. An embayment in the ice cliff usually coincides with an upwelling because meltwater enhances calving of the tidewater front (e.g., Sikonia and Post 1980). Also at the upwelling, icebergs are pushed away from the glacier by the overflow current, and sea gulls feed on shrimp and plankton.

On August 3, 1985, the stream upwelling was a brackish overflow with a sharp pycnocline between 5 and 10 m depth (Fig. 2). In the overflow, suspended sediment concentrations exceeded 1.3 g/L but dropped to below 0.8 g/L at 10 m depth. During a given sampling interval, the highest sediment concentrations were usually measured from at or near the upwelling. A progressive increase in sediment concentration during the summer was observed, reflecting the increase in meltwater discharge.

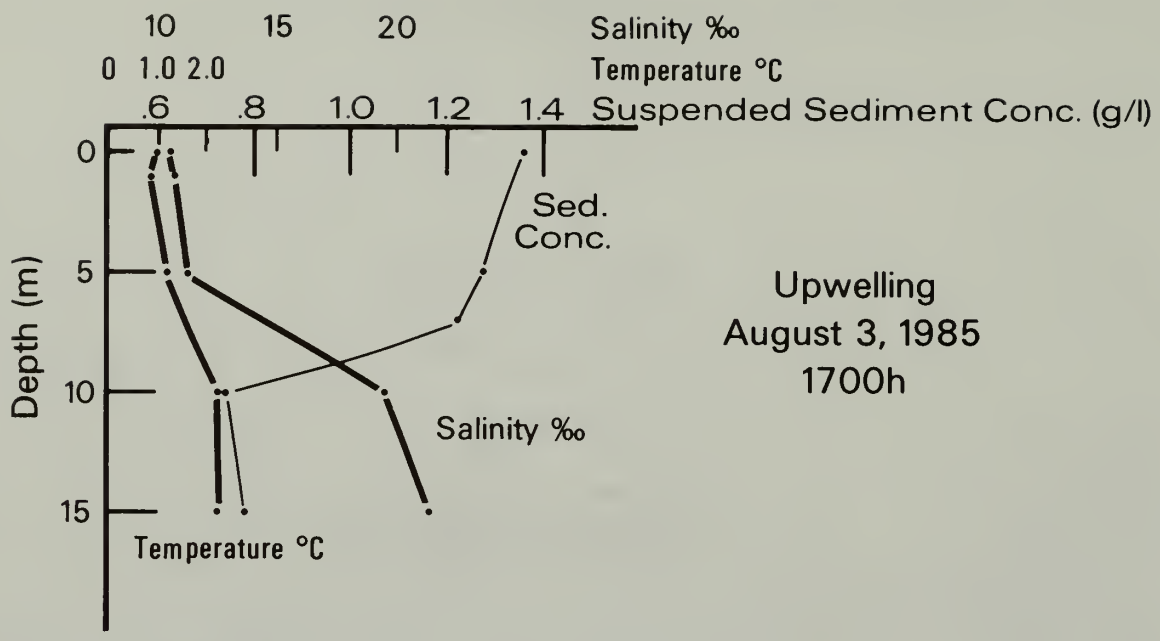

Fig. 2. Salinity, temperature and suspended sediment concentrations within the upwelling on August 3, 1985 at McBride Glacier.

Suspended Sediment Transport

Suspended sediment is transported from the upwelling downfjord in a turbid, lower salinity surface layer. The turbid overflow occurs above the pycnocline and ranges in thickness from 8 to 20 m. Vertical variations in total suspended sediment concentration and sand concentration were determined from water samples collected from closely spaced depths at an anchor station 400 m from the terminus. A profile from July 12, 1986 shows the typical condition; the maximum near-surface sediment concentration was beneath the water surface, at 6 m depth (Fig. 3). Wind produces turbid surface plumes that are readily visible. However, much higher sediment concentrations always occur deeper in the surface layer regardless of wind activity. Local zones of surface turbidity also result from upward transport of underlying highly turbid water by internal turbulence within the overflow. Restricted turbid zones are also observed in turbulent eddies on the lee of large icebergs and in boat wakes. This process was also described by Wright (1887, p. 16) from Muir Inlet:

> The steamer's screw brought up much muddy water from below the surface some distance down the bay, and where the surface was clear.

Suspended sediment transport in glacial fjords is controlled by: (1) momentum of the stream discharge, (2) a thick overflow and (3) rapid rate of flocculation. Submarine discharge enters the fjord as a jet which penetrates a short distance into the fjord, at depth, until buoyancy forces dominate and the turbid water rises to the surface as a plume. Discharge momentum is transferred to the overflow near the upwelling, and downfjord of this point, the overflow is a barotropic current because of the freshwater head near the glacier. This produces a thick overflow with highest current velocities below the surface.

Mixing of meltwater with fjord water at the efflux rapidly increases the salinity. Therefore, by the time the plume reaches the surface, it is brackish (>5‰) and the salinity is sufficiently high for flocculation to begin. As particles increase in size due to flocculation, they sink deeper within the near-surface layer. Transport and release of suspended sediment from the near-surface layer is tidally controlled. A decrease in horizontal velocity at low tide allows particles to begin their vertical descent through the water column. Coarser grains, such as sand and coarse silt, settle individually, and finer flocculated particles settle as turbid layers. A turbid layer is shown at 25 m depth in Fig. 3.

Circulation

Meltwater discharge and tides control circulation within McBride Inlet. The glacier's influence on the water column is shown by the inlet's narrow salinity and temperature range. Profiles collected during May through September and in January showed salinities of between 4 and 32‰ and temperatures between 0 and 4.2°C. The water mass with the highest salinity and temperature originates in Muir Inlet.

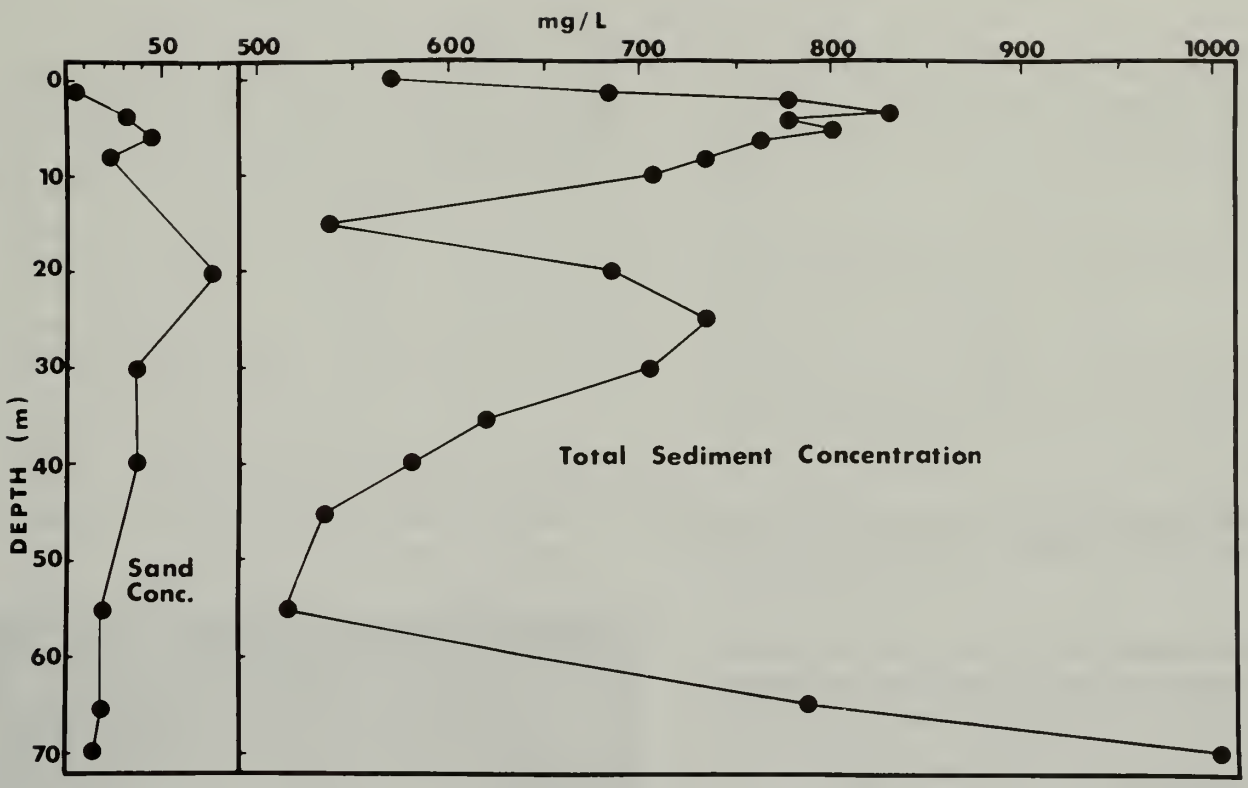

Fig. 3. Suspended sediment concentrations and sand concentrations at a station 400 m from McBride Glacier on July 12, 1986.

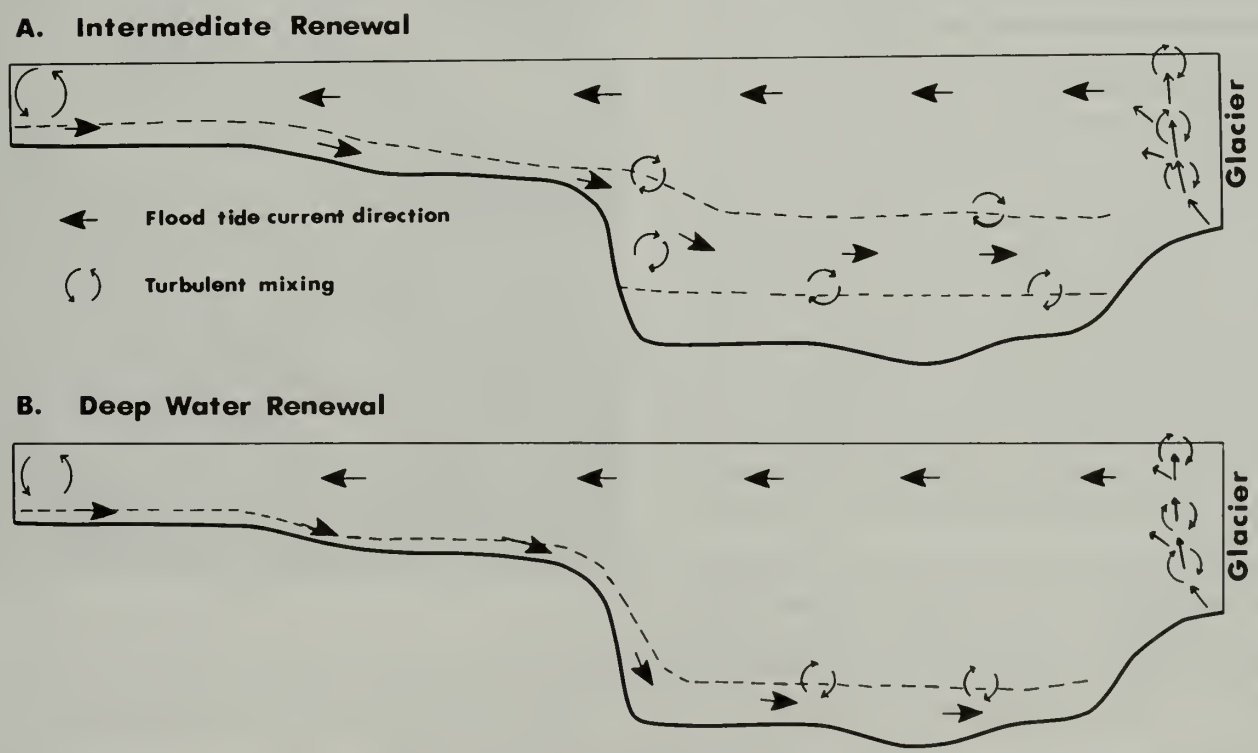

Fig. 4. Schematic diagram of flood tide circulation in McBride Inlet. Two types of circulation can occur, intermediate water renewal (A) during winter and spring and deep water renewal (B) during summer.

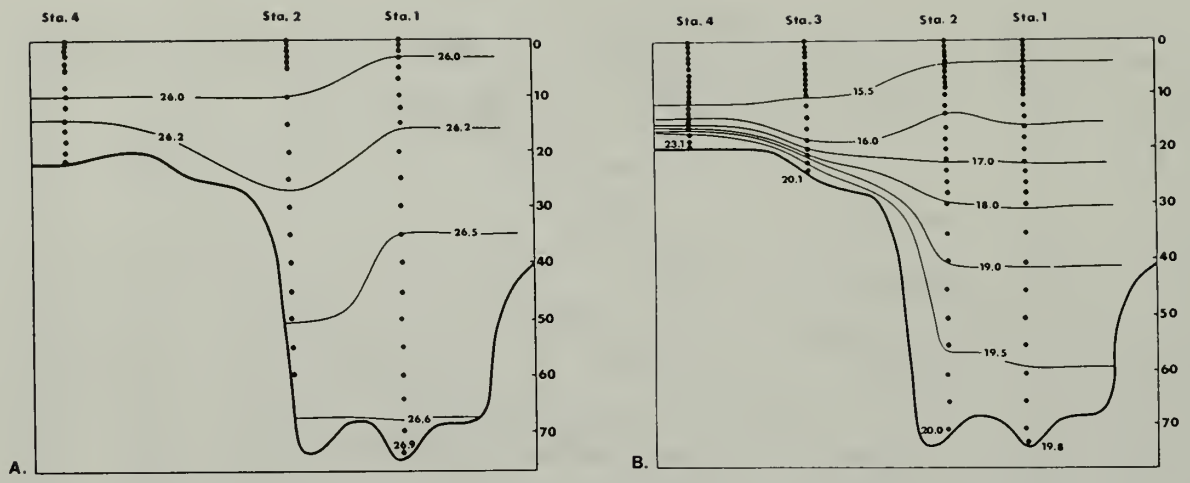

Fig. 5. Distribution of water density (sigma-t) within McBride Inlet during intermediate water renewal (A) and deep water renewal (B). Data in (A) was collected at high tide on June 26-27, 1986.

Figure 4 is a schematic diagram of flood tide circulation within McBride Inlet based on current measurements at anchor stations. These interpretations are supported by longitudinal profiles of salinity and temperature at 3 or 4 anchor stations (Fig. 5).

The surface layer varies in thickness depending on the amount of discharge. Surface flow is always directed out of the inlet at velocities between 5 and 20 cm/s. Over the sill the bottom current reverses direction on ebb tide so the entire water mass flows outward.

Intermediate water renewal (Fig. 4A) occurs from fall through early summer when deep-basin water is dense. During each flood tide, dense water is added over the sill. When the density is less than that of the deep basin, flood water flows in under the outward flowing surface layer. An example of intermediate water circulation is shown by density (sigma-t) distribution in January 1986 (Fig. 5A). In winter, the water column is homogeneous, and deep water is denser than the near-surface water crossing the sill on flood tide. Deep water renewal occurs as soon as the density of the water crossing the sill exceeds that in the deep basin (Fig. 4B). This condition occurs during summer because submarine discharge lowers the density of the deep basin below that of the incoming flood water.

The incoming bottom current is important in maintaining a near-bottom layer of high suspended sediment concentrations (a nepheloid layer) within the deep basin. The nepheloid layer occurs only during renewal. An example is shown in the suspended sediment profile from July 12, 1986 (Fig. 3).

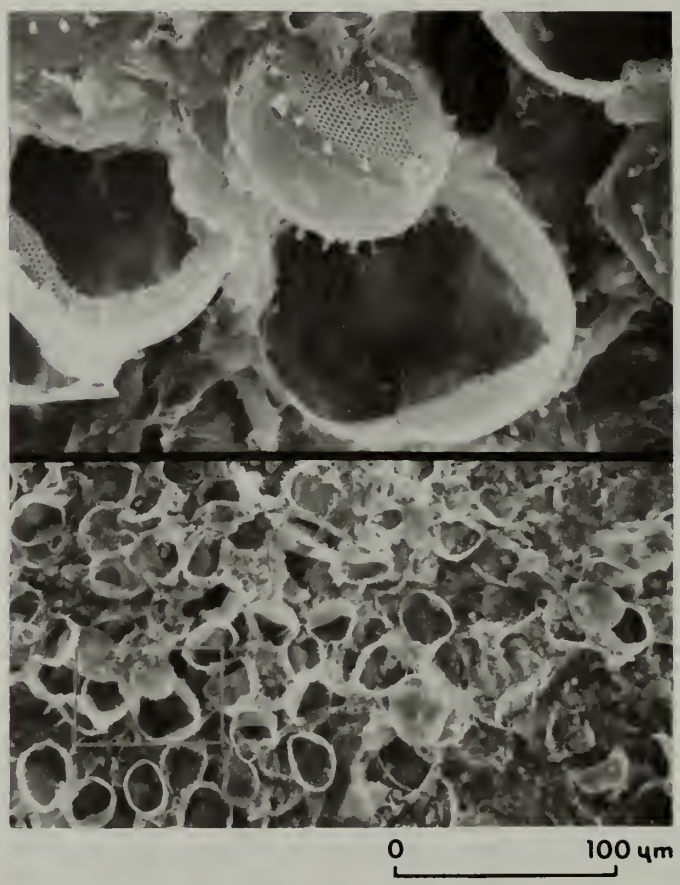

Fig. 6. Photomicrograph of diatoms (*Thalassiosira pacifica*) in a water sample from Muir Inlet. The 3.5 L sample was collected from 3 m depth on July 21, 1987. The concentration of suspended particles was 4 mg/L.

Discussion

Circulation and suspended sediment dynamics within glacial fjords are important controls of sediment deposition rates, sedimentary deposits, and on plankton production. Weak fjord stratification produces a tidally-influenced, partially mixed estuary that favors high ice-proximal sedimentation rates and deposition of cyclically interlaminated sediments. Sedimentation rates as high as 20 m/year occur at the terminus (Cowan 1988). These high rates drop off exponentially with distance from the subglacial stream because low current velocities in the near surface layer are unable to transport the coarse sediment load very far away from the terminus.

Tidal control on release of suspended sediment from the near-surface layer both increases ice-proximal sedimentation rates and deposits rhythmically interlaminated sediment on the fjord floor. These deposits, termed cyclopsams and cyclopels, were first described from Muir Inlet by Mackiewicz et al. (1984). Cyclopsams are thick fine sand/mud couplets more common proximal to an efflux, and cyclopels are thin very fine sand and silt/mud couplets more common in areas distal to an efflux. Suspended sediment traps, deployed within McBride Inlet, collected two couplets each day resulting from particle release and sorting from the two low tides. Additional laminae were sometimes collected because of transport of sand and coarse silt by high discharges.

Submarine discharge from tidewater termini produce favorable conditions for phytoplankton. Nutrients are cycled to the surface by vertical entrainment of deep, nutrient-rich water in the upwelling. Transport of suspended sediment as a plume beneath the surface allows growth in the upper 4 of the water column because light is not restricted. These factors produced a diatom bloom of *Thalassiosira pacifica* that extended downfjord from within 0.25 km of the tidewater terminus of Muir Glacier during mid-July 1987 (Fig. 6). Diatoms have also been collected from the water column proximal to McBride Glacier.

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Iceberg-Rafted Debris in McBride Inlet, Glacier Bay, Alaska

by

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Abstract

Sedimentary rocks are used by geologists as interpretive tools in understanding ancient environments. By studying processes of modern sediment accumulation in front of marine-ending glaciers, we should be able to infer the termini positions of paleoglaciers from the sedimentary record they leave. Marine sedimentation in temperate glacial settings is characterized by locally high deposition rates (>9 m/year) and the presence of dropstones, which are pebble- to boulder-sized clasts rafted by glacial ice. Such iceberg-rafted debris (IBRD) ranges in size from dropstones down to clay and is generally released from bergs suddenly when melting causes rolling, break-up, or debris flows from the ice. The proportion and character of this IBRD are potentially useful tools in estimating the distance from a tidewater terminus. Characteristics of the debris are dependent on mode of glacial transport. Basal debris is highly abraded, and consequently, clasts are generally well rounded and often contain facets. Supraglacial debris is angular due to passive transport after originating from rockfalls onto the glacier surface. Englacial debris derives from both basal and supraglacial sources, and clasts have a range of roundness. Differences of IBRD proportions within bottom sediments are controlled by berg paths through the fjord. Larger bergs from McBride Glacier are of basal origin, contain the greatest proportion of debris (93%), and have their movement controlled by fjord currents that in McBride Inlet move in a gyre proximal to the glacier. A sill or bathymetric high in McBride Inlet constrains the distance of transport of bergs with basal debris away from the glacier. Smaller blocks of ice, or brash ice, comes from supraglacial and englacial positions, travels in surface water currents, and releases debris by particle-by-particle meltout. A stratigraphic record from an environment similar to McBride Inlet should contain lenses of IBRD hundreds of meters wide that are produced from dumping of debris-laden bergs trapped in a gyre. Commonly, gyres concentrate bergs so that specific locations will receive greater proportions of IBRD. As smaller bergs move away from the glacier face, melting releases individual clasts so that there is a regular decrease in IBRD with distance downfjord. The presence of angular and rounded debris in the proximal setting, pods or lenses from episodic dumping, and horizons containing higher proportions of angular debris from intense calving events of ice with high concentrations of supraglacially-derived debris are all unique to tidewater settings. They distinguish this setting from the ice shelf environments of colder climates.

KEY WORDS: Ice rafting, glacimarine sedimentation, tidewater glaciers, dropstones, diamictons, pebbly mudstones.

Dropstones and other rafted debris in geological outcrops have been used by geologists to infer glacial settings. Quantification in changes and characteristics of iceberg-rafted debris (IBRD) with distance has never been undertaken in modern settings. Documenting these changes will allow geologists to determine the relative position of paleoglacial termini from the rock record. This study, conducted over the summers of 1987 and 1988, will prove useful in the interpretation of paleoglacimarine deposits through sampling of known ice-rafted sediments. Inherent problems associated with direct collection of IBRD were attempted to be minimized by establishing two independent methods of quantification. Firstly, shallow, 0.5-m^2 sediment traps were suspended just above the bottom of McBride Inlet at six locations, and IBRD was recovered daily or bidaily. Secondly, bottom-sediment grab samples were collected using an Ekman box-corer, and

proportions of IBRD were calculated as a percent of total dry weight. Suspended tubes were used to determine hemipelagic sedimentation rates. Particles larger than medium sand (>0.5 mm) were considered to have been ice-rafted. Although finer size fractions are rafted, they were not differentiated from particles deposited by suspension settling and, therefore, were not included in trap and bottom grab results.

Source of Glacial Debris

The numerous debris sources within McBride Glacier reflect the high variability of size, shape, and rock type of interpreted IBRD deposits. Debris is transported in basal, englacial, and supraglacial positions of the glacier (Fig. 1). Basal debris extends 12 to 15 m upwards from the base of McBride Glacier. Englacial debris occurs between the basal zone and the surface where supraglacial debris occurs. Specific sources for debris include the following in order from supraglacial to subglacial positions (summarized in Table 1):

1. South-lateral supraglacial and englacial debris contribute about 1% of total IBRD. Clasts are angular to rounded and are dominated by granites. The source of clasts is a "medial" moraine in which debris is quite diffuse, with 1 to 10% concentrations in the ice.

2. Concentrations of englacial stratified-debris vary from 6 to 38%. The debris is angular to rounded with pebbles of various rock types, and contributes < 1% to total IBRD volume. Individual debris layers are nearly 0.1 m thick and are usually found near the basal zone/englacial zone contact.

3. Dispersed or very disseminated, north and south, englacial debris is characterized by low concentrations (< 0.1%) of angular granitic pebbles and widely dispersed mud balls. This zone contributes < 1% to total IBRD.

4. Medial englacial and basal debris have high proportions of marble clasts that increase in roundness in the basal zone where more active transport occurs (c.f. Boulton 1978). Black mud, angular sands, and angular to rounded pebbles from the medial moraine contribute about 5% to total IBRD within McBride Inlet. Debris concentrations between 1 and 70% occur in layers which vary in thickness between 0.1 and 1.0 m within the ice.

Medial debris melted-out supraglacially is about 70% marble and has clasts up to 1.5 m across. The supraglacial medial moraine is 160 m wide at a distance of 3 km from the terminus. Debris is only one clast thick on the surface,

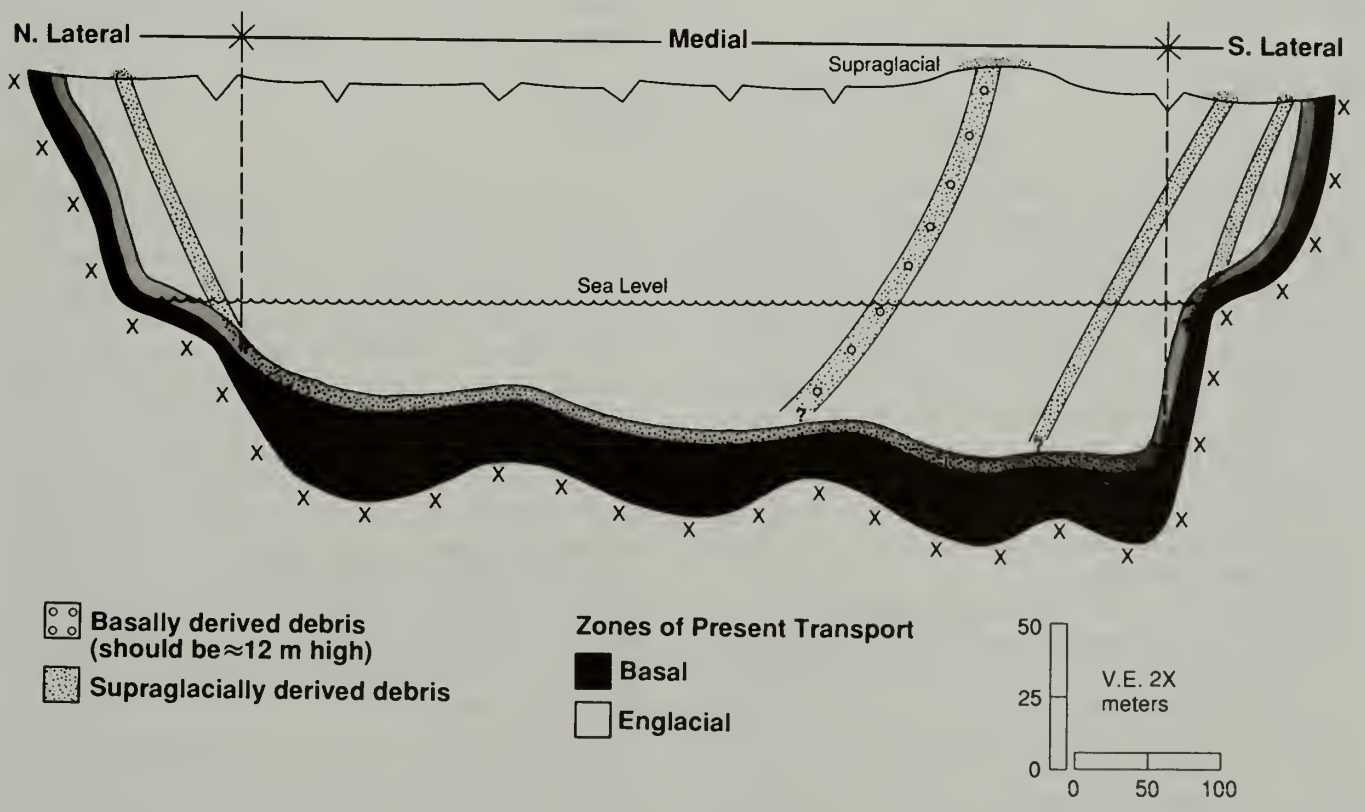

Fig. 1. Cross-section of the face of McBride Glacier showing sources of the debris that becomes iceberg-rafted.

Table 1. Concentration of debris in ice taken as the percentage of debris water volume of melted-ice, diagnostic clast roundness, presence of facets and major rock types, and proportion of IBRD in bottom sediment (as a weight percent) for debris from different locations in McBride Glacier.

Debris source	Debris concentration in ice (%)	Clast roundness and characteristic rock type	Proportion of IBRD in bottom sediment (%)
South-lateral englacial and supraglacial	1-10	angular/granite	1
Stratified englacial	6-38	angular-rounded/ various	1
Dispersed englacial	< 0.1	angular/granite	< 1
Medial englacial and basal	1-70	angular/marble	5
Dispersed basal	< 0.1	angular/various	< 1
Stratified basal	4-90	rounded + facets/ various	12
Basal diamicton	>95	rounded + facets/ various	80
Marine outwash	100 (on ice)	well rounded/ various	1

but about 1.4 x 104 m^3 of debris were estimated on a 1-m-wide transect across the moraine. Most of this volume falls down crevasses during transport to the terminus and probably becomes dispersed englacial debris. The portion that remains on top of the glacier is dumped during calving at the front and added to the morainal bank directly at the terminus.

5. Dispersed basal debris also has very low concentrations but includes angular granite, marble, and andesite pebbles with local dispersed mud balls. Layers of this debris are interstratified between debris-rich layers in the basal zone. Basal dispersed zones are differentiated from (3) by the decreased air-bubble content in the ice because it formed under higher pressures.

6. Stratified basal-debris is generally rounded, contains faceted or flat-sided pebbles, and has highly variable rock types. Debris content decreases within individual stratified ice and debris layers from their base upwards. Debris content ranges from >90 to < 5%, and contributes about 12% to total IBRD. Individual debris layers, which have thicknesses between 0.05 and 0.3 m, locally show grading, pebble alignment, and an absence of clay-sized particles, indicating that the layers probably originated by regelation (freezing onto the glacier sole) of sediment that had undergone water transport. Average thickness of this zone is about 12 m, and often three or four distinct layers of ice plus debris are separated by ice with dispersed mud. The dispersed-mud zone of a glacier has been named the amber-ice zone and is believed to be the result of upward movement of clay particles during recrystalization (c.f. Drewry 1987). McBride Glacier has as many as eight individual ice and debris layers.

7. A solid debris layer occurs at the very base of the glacier and is observed in basal bergs that calve from submarine positions and rise to sea level. The layers are compacted diamicton with nearly equal amounts of mud, sand, and pebbles and are up to 1.5 m. thick. These layers are the largest contributors of IBRD within McBride Inlet (80%), and because they are highly compacted, blocks can break off and fall through the water column to be deposited as a single pod within hemipelagic mud.

8. Marine outwash is deposited on projections of basal glacier ice by a subglacial or englacial stream and is preserved on top of bergs after they calve from this submarine position. The outwash generally shows a bimodal size distribution, is unfrozen, has no clay, and contains well rounded, elongate

pebbles with preferred long-axis orientation. Gravels commonly occur in sharp contact with graded, very coarse to coarse grained sands. The contribution to total IBRD is about 1%.

Debris Concentration

Basally transported pebbles often show facets, striae, or chatter marks indicative of active transport. Within McBride Inlet, these features occur mainly on the softer marble pebbles. Facets occasionally occur on the moderately hard basalts but are rare on granites. Clast roundness is much higher in basal debris as corners and edges are abraded. Transport by subglacial streams rapidly decreases pebble size, increases roundness, and abrades away surface features (c.f. Liu, from Drewry [1987], p. 68). Except for the medial moraine which has about 70% marble, different areas of the glacier do not possess preferred rock types. North and south basal debris contains mostly angular granite but contributes only minor amounts of IBRD. Because roundness increases with distance of basal transport (Boulton 1970), this lateral basal debris, which is quite angular, must be locally incorporated in the glacier near the terminus.

Berg Trajectories

After ice is calved from McBride Glacier, its flow paths are controlled by fjord currents and wind. For this study, calved ice is grouped into two broad categories based on size. Large blocks of ice, termed bergs, rise more than 1 m above sea level. Smaller sizes are termed brash ice.

Bergs from McBride Glacier commonly rise between 2 and 4 m above sea level and are controlled by currents between 8 and 16 m depth (c.f. Weeks and Mellor 1978). Consequently, berg movements are controlled by fjord currents that are generated by flood and ebb tides and the outflow of the surface brackish layer originating from the meltwater stream discharge. A gyre is formed by higher-density flood tide currents which are bathymetrically controlled. A shoal near mid-inlet forces incoming waters to the north creating a clockwise rotation in the gyre (Fig. 2). The gyre is elliptical, about 600 m in circumference, and has current velocities of up to 12 cm/s.

Bergs have been seen to circulate in the gyre in McBride Inlet for up to 10 days. Generally the bergs are from the basal zone and are debris laden. During circulation, bergs undergo melting from fjord waters and become unstable causing

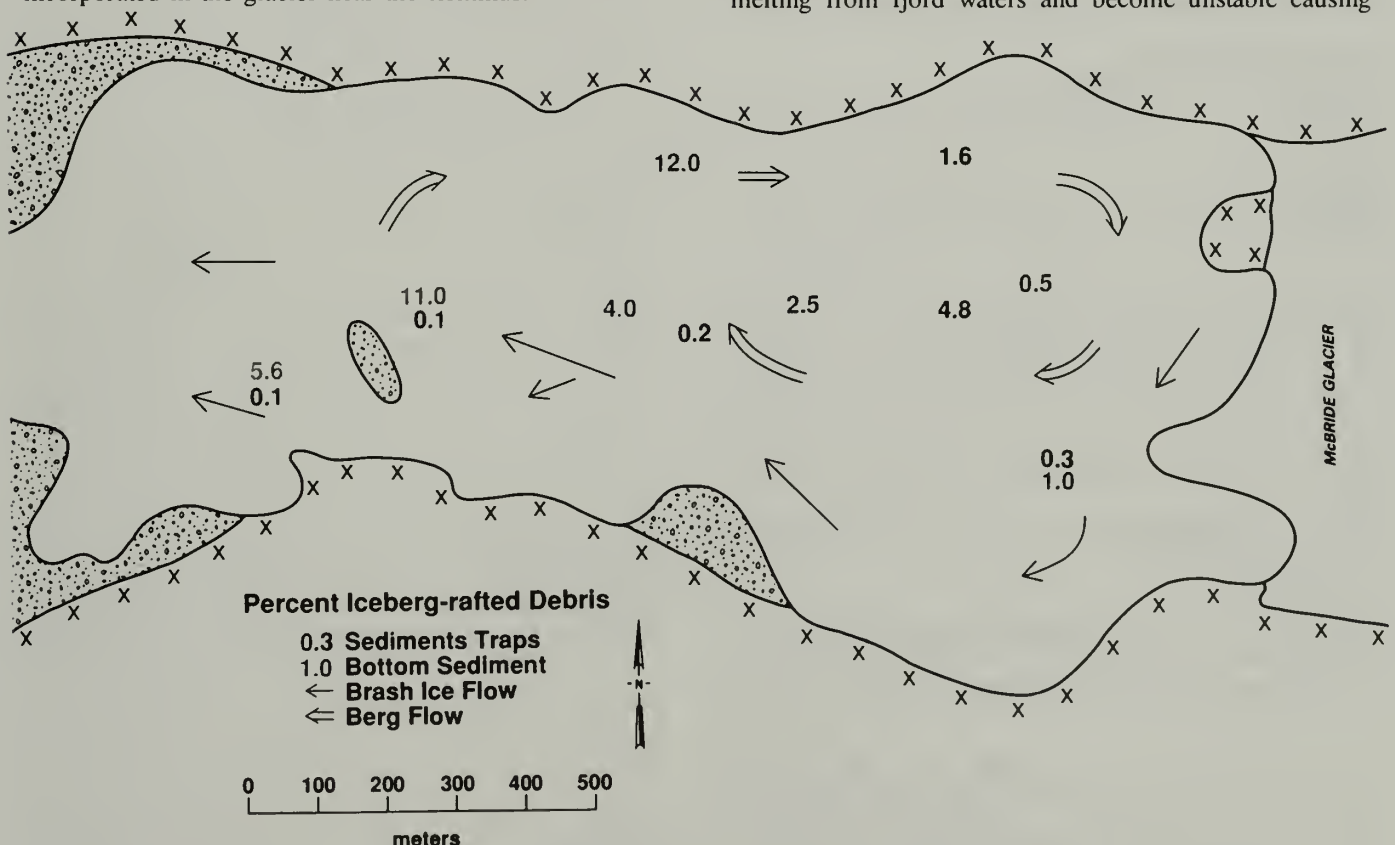

Fig. 2. Trajectories of calved ice within McBride Inlet (arrows). Berg movements are controlled by currents at 8 to 16 m depth, and brash ice is moved by surface currents and wind. Average concentrations of IBRD (numbers) are determined from sediment traps and bottom-sediment grabs.

dumping of debris during roll-dumping or when they break up. The debris that has been exposed or has accumulated in ice depressions is released suddenly and can be expected to deposit pods or lenses of IBRD. Release of the basal solid debris layer, which accounts for a large proportion of all IBRD, should also create a pod or lens when it drops as solid blocks.

Decreased depths at the western edge of the gyre strand bergs during falling tides. The gentle slope off the shoal (Fig. 3) and the macrotidal prism accentuate this event. During stranding, bergs often roll, tilt, or are washed over by calving waves, depositing higher proportions of IBRD in this zone of shallower (15 to 30 m) water. Ultimately, IBRD deposition is directly related to the time that a berg spends in an area; thus, areas of grounding or areas within the gyre have greater frequency of IBRD deposition.

Brash ice is moved by wind and surface currents. Katabatic winds blow off the glacier and push the brash ice out of the inlet as fast as 20 cm/s. Barotropic surface flow, generated by the meltwater stream discharge, creates tightly defined bands of brash ice transport. Occasionally brash ice is entrained behind larger bergs, but normally it flows out the inlet or to distal areas of the inlet where velocities of water currents and katabatic winds are greatly decreased.

Brash ice generally contains englacial and supraglacial debris. Particle-by-particle meltout of these more angular clasts creates an area in the outer basin with individual angular sand grains or pebbles dispersed throughout a mud matrix. Occasionally smaller blocks of basal ice are driven to the outer reaches of the inlet and release more rounded debris there.

Sediment Trap Samples

About 50% of sediment traps deployed in the inlet were dragged into shallower water where they would either overturn, plow up bottom sediments, or be dragged from their original positions making the data useless. If a roll-dump or a large boulder-drop occurred over a trap, it became impossible to retrieve due to its weight; consequently, limits to amounts of IBRD were unintentionally created.

A definite decrease in shallower water of average clast size, pebble proportion, and largest clast size can be attributed to the fact that traps could not remain suspended under large bergs in shallower water. Samples of large IBRD events such as roll-dumps were retrieved from within deeper portions of the inlet. In outcrops, these deposits would appear as pods of unsorted gravel in a mud matrix.

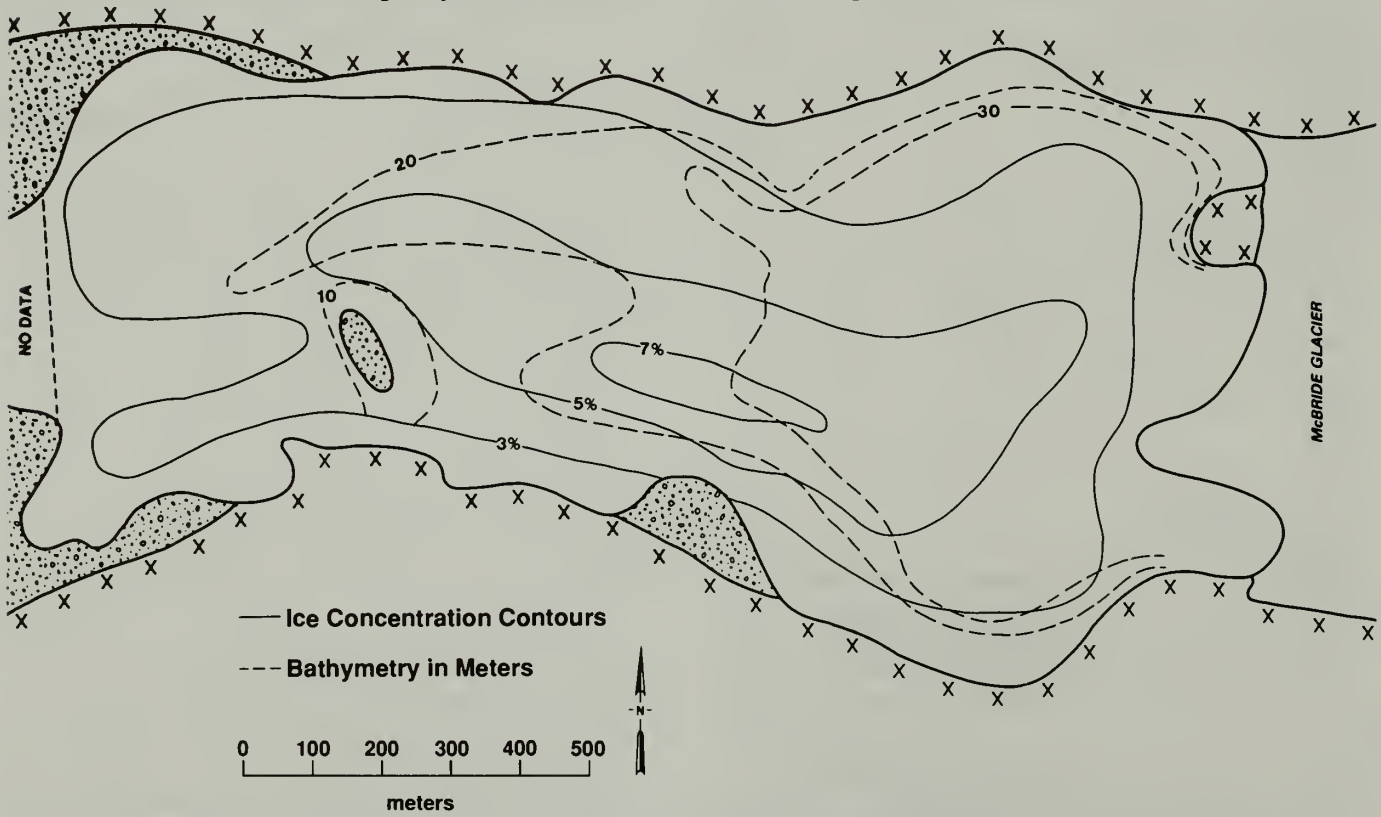

Fig. 3. Average proportions of water surface area covered by calved ice in McBride Inlet. Highest concentrations of ice occur where paths of bergs and brash ice overlap in the southwestern area of the ice-proximal basin. Depth contours show the sill where bergs ground during ebb tides on the west side of the ice-proximal basin.

Analysis of sediment trap samples shows the episodic nature for IBRD release; proportions of IBRD within bottom sediment vary from < 0.1 to >90% by weight. Average values of the six sites are shown in Fig. 3. As stated above, higher proportions of IBRD occur in the center of the gyre where debris-rich bergs are found in greater frequency. Because the geometry of the gyre changes with tidal stage, bergs are always at the center at any time, while fringe areas of the gyre sometimes experience no IBRD input.

The higher proportion of IBRD collected in a small number of sediment trap samples indicates most deposition occurs by roll-dumping. Bottom sediment grab samples reinforce sudden release of IBRD as a major mechanism for its deposition within McBride Inlet. Particle-by-particle contributions cannot be fully evaluated without a more thorough analysis of finer particle sizes. Smaller, less debris-laden bergs cover areas with greatly decreased marine rock flour (hemipelagic glacial mud) deposition. In these more distal areas of the inlet, more IBRD originates from single particle falls.

Bottom-sediment Grab Samples

Successful Ekman box-core samples contain mostly mud (about 95%) with dispersed sand and pebbles. In areas of high IBRD concentrations, larger pebbles were caught in the jaws of the box corer causing loss of the finer sediment, and IBRD proportions are impossible to calculate. Of the 50 Ekman attempts, 7 were affected in this manner. Sampling of bottom sediment does not differentiate between IBRD and mass flow deposits common to the fjord environment (Powell 1981). Samples containing a single rock type of angular pebbles and graded sands, which are inferred to be from mass flows of bottom sediment (e.g., turbidites), are not included in present results. Resedimentation deposits of IBRD may not be currently recognized in samples and may account for differences between trap and grab samples.

The proportions of IBRD in over 30 bottom-sediment grab samples show a high degree of variability. Concentrations range from < 1 to >85%, which agrees with the highly variable IBRD concentrations in sediment traps. Calculated values from grab samples show that 65% of IBRD is coarser than sand, which is in agreement with weight proportions collected directly from bergs.

Highest concentrations of IBRD in bottom-sediment grab samples are on the sill just outside the deep ice-contact basin and in areas under the central gyre. On the sill, concentrations of IBRD are as high as 53%, and maximum clast size is 10 cm, which for these samples is limited by the dimensions of the box corer.

Summary

Deposition of IBRD in McBride Inlet is controlled predominantly by trajectories of debris-laden basal bergs through the fjord. Berg circulation in an ice-proximal gyre and grounding of bergs on the sill at the western edge of the gyre during ebb tide create areas where the likelihood of berg roll-dumping is increased. Large amounts of debris are released by these events creating pods or lenses of more rounded debris in marine rock flour. Particle-by-particle meltout occurs and becomes more important distally where total sedimentation rates are about 5% of proximal rates. Individual particles melted out in distal areas are likely to be more angular and smaller than more ice-proximal IBRD deposits.

Very angular clasts of a single rock type (marble) are deposited throughout the inlet after a large calving event from the medial moraine portion of the glacier. Such events could form identifiable horizons in the stratigraphic record. Those horizons as well as proximal deposition of supraglacially derived debris, roll-dump structures, and mixing of subglacial and supraglacial debris can all be used as diagnostic criteria of a tidewater front environment in a temperate glacial regime. These criteria differ from those of a polar regime where deposition is from ice shelves (c.f. Powell 1984).

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The Effects of Surging on a Proglacial Lake: Carroll Glacier, Wachusett Inlet

by

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Abstract

Carroll Glacier, with termini at the heads of both Queen and Wachusett Inlets, surged in 1919, 1943, 1966, and most recently in 1987. During studies of glacimarine sedimentation in Wachusett Inlet during the summers of 1987 and 1988, observations were made of the effects of the surge on a proglacial lake recently isolated from the fjord. During the period of observations, the glacier advanced more than 1 km over the lake basin, producing extremely high suspended sediment concentrations (> 9 g/L measured) in the lake water and local sedimentation rates of up to 22 cm/d. A push moraine developed in early July 1987 and remained a prominent feature throughout the continuation of the advance. A variably thick layer of homogeneous silty mud was deposited over the lake basin during the period of most rapid surging. By summer 1988, the advance had greatly diminished, and the remaining lake basin (about 25% of the original area) was slowly uplifted. By the end of August 1988, most of the lake floor was exposed and undergoing rapid erosion by meltwater channels.

KEY WORDS: Glacilacustrine sedimentation, glacial surges, proglacial lake, Carroll Glacier, push moraine, surge behavior, surge glaciers.

Carroll Glacier, a relatively large valley glacier about 42 km in length and 200 km² in area, presently terminates at the heads of both Queen and Wachusett Inlets. Observations during the present century have shown that Carroll surged in 1919, 1943, and again in 1966, suggesting a recurrence interval of about 23-24 years (Field 1969). During field studies of deltaic and marine sedimentation in Wachusett Inlet in summer 1987, we became aware that the Carroll terminus was again advancing rapidly at its Wachusett margin.

Prior to about 1980, the glacier was in direct contact with marine waters of Wachusett Inlet. Subsequently, a headward portion of the inlet became cut off and isolated by rapidly growing outwash fans, forming a proglacial lake which in June 1987 was approximately 1.3 km² in area. On June 9, 1987, an overflight of the area resulted in several photographs of the lake and glacier terminus. The lake was later surveyed by plane on July 1, although we were unaware that a surge was already underway because our June 9 photographs were not yet developed. We measured depths and salinity-temperature profiles at 5 locations in the lake and collected 11 water samples for measurement of suspended sediment concentration. The lake was not visited again until July 31, 1987, when it became apparent for the first time that the glacier terminus was moving rapidly over the lake basin. Observations were then continued intermittently through August 1987 and again between late June and late August 1988. No investigations of the glacier itself were undertaken.

The Advancing Terminus

Figure 1 shows successive positions of the Carroll terminus in contact with the proglacial lake between June 9, 1987 and July 6, 1988. No other portions of the terminus were mapped, although it was clear that the entire margin facing Wachusett Inlet was advancing generally toward the fjord. The June 9 position is estimated from oblique serial photographs whereas the four subsequent positions were surveyed in the field. Between June 9, 1987 and July 6, 1988, the mapped portion of the terminus advanced on average slightly more than 1 km.

The greatest movement was between June 9 and July 1, 1987, covering average and maximum distances of 640 and

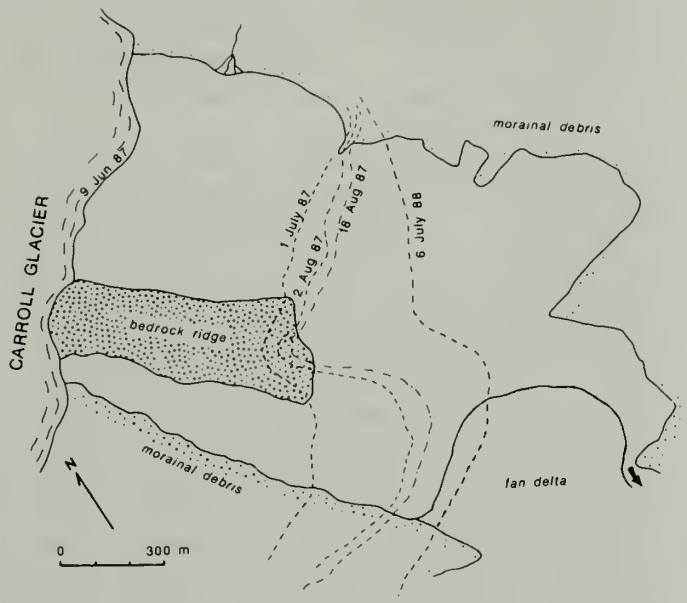

Fig. 1. Outline of proglacial lake showing successive positions of Carroll Glacier terminus. Wachusett Inlet lies to the southeast.

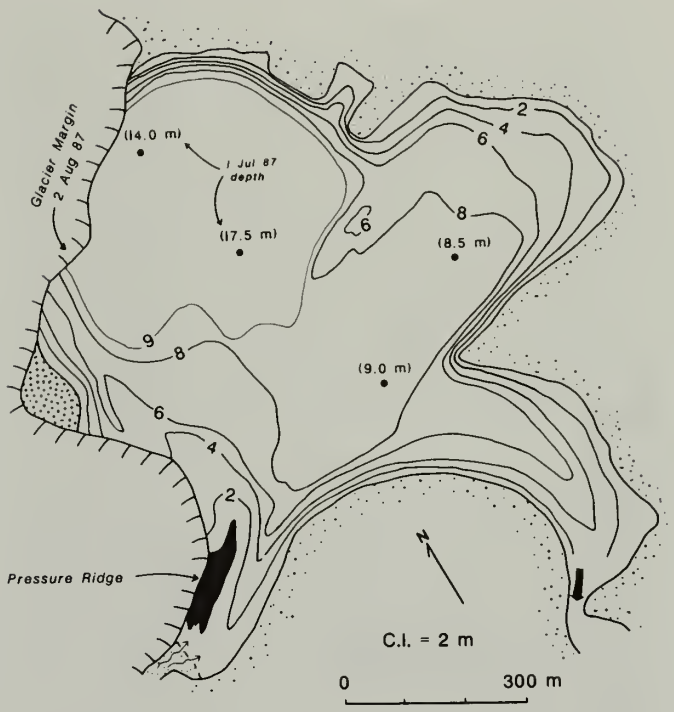

Fig. 2. Lake outline and bathymetry on August 5, 1987. Large dots indicate depths sounded by marked line on July 1, 1987.

750 m, respectively, at calculated velocities of 29 and 43 m/d for the 22-day interval. We have not determined the terminus position prior to June 9, 1987; thus, the successive positions shown in Fig. 1 represent minimum travel distances from the point on initial surging.

Effects of Advance on Lake (1987)

Because the lake outlet supplied one of the three main streams feeding sediment and water to the fjord, our initial interest in the lake arose from its role as a possible sediment sink. On August 5, 1987, lake bathymetry was mapped by 13 surveyed acoustic profiles. Results indicated two virtually flat basins, one circular in shape, 9.5 m deep, lying in the north portion of the lake, the other approximately elliptical, about 8.5 m deep, lying to the south and abutting the outlet arm (Fig. 2). Four of the 5 depths sounded on July 1 are indicated on Figure 2 (a fifth sounding location was covered by the surging ice). Comparison of these depths, measured 36 days earlier, with the August 5 bathymetry map shows remarkably high sedimentation rates in the north basin: approximately 4.5 m in one location and 8 m at the other, yielding time-averaged deposition rates of 13 and 22 cm/d, respectively. In comparison, the two sounded locations in the more distal south basin indicated deposition of about .5 m or less over the same period. It should be noted that the lake bottom was highly underconsolidated and "soupy," indicating rapid sedimentation and also precluding the July 1 sounding depths from being measured more accurately than to the nearest 0.5 m. The extremely rapid sedimentation in the north basin suggests that deposition was caused largely by sediment gravity flows filling in topographic lows. Such flows may have been generated by (1) lake bottom sediment pushed forward by the advancing ice or (2) icebergs both impacting and dragging across the lake floor, causing sediment liquefaction and slumping. Large grounded bergs were especially abundant in the north basin throughout the period of observation.

Water temperature profiles showed essentially isothermal conditions in the lake with slightly warmer temperatures near the surfaces at some locations (Fig. 3). Salinity profiles, to determine whether sea water had been entrapped when the lake was isolated from the fjord, showed that the lake water was entirely fresh. By 1987, the lake surface was well above the range of high tides.

Suspended sediment concentrations, measured in water samples obtained at different depths in the water columns, showed extremely high values. Concentrations in 11 samples collected July 1, 1987 at four locations averaged 4.0 g/L, and two samples contained concentrations exceeding 9 g/L (one is shown in Fig. 3, left). Considering that suspended sediment concentrations in glacial lakes are usually measured in mg/L and are almost never reported to exceed 1 g/L (e.g., see Table

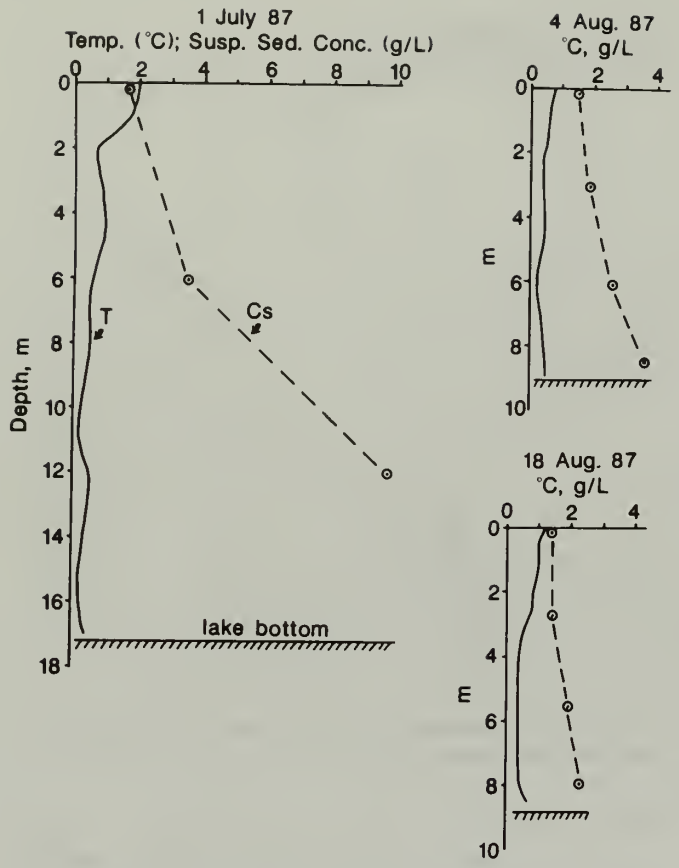

Fig. 3. Temperature profiles and suspended sediment concentrations at Loc. III (marked as "17.5 m" site in Fig. 2) on three successive dates. Note great decrease in depth between 1 July and 4 August, caused by rapid sedimentation associated with surge. Note also generally decreasing suspended sediment concentrations with time.

1 in Gilbert and Desloges 1987), these values are remarkable. Repeated sampling at one locality in the north basin showed generally decreasing concentrations of suspended sediment from July 1 to August 18, 1987 (Fig. 3). This corresponds to the slowing rate of advance (Fig. 1) and, presumably, slowing rates of fine sediment released by the glacier and/or reentrained by disruptions of the lake bottom.

Only one principal inflowing stream, located in the southwest corner of the lake (Fig. 2), was visible during August. This stream accounted for about one-fourth to one-third of the total lake outflow. Outflow was monitored by a stage recorder at the lake outlet August 1-21 which indicated discharges ranging from about 8 to 17 m^3/s. Attempts to locate subglacial stream sources by suspending a current meter from a boat near the ice margin were unsuccessful. Most of the lake water appeared to be derived from a number of small streams entering at points along the highly crevassed terminus. Density underflows were searched for at numerous locations using the same current meter but were located only near the mouth of the aforementioned stream.

One striking morphological effect of the surge was a ridge of uplifted lake bottom which, when first observed on July 31, was about 50 m long, less than one meter above lake level, and situated about 30 m in front of the terminus. The ridge was not in direct contact with the glacier and appeared to have formed by upward pressure induced by the weight of the glacier and transmitted outward and upward through the plastic lake sediment. By August 2, this pressure ridge had roughly doubled in length, increased in height to over 3 m locally, and was connected to the terminus by additional exposed lake floor (Fig. 2). The ridge continued to grow daily, and by August 20 it had attained a maximum height of 9.9 m. By this time the terminus had advanced an additional 50 m, overtaking the pressure ridge and "snowploughing" it forward to produce compression features typical of push moraines (Boulton 1986; Kruger 1985). Numerous slumps and debris flows were shed lakeward of the push moraine as the glacier continued to advance. Interestingly, the pressure/push ridge was developed only along the southwest portion of the lake.

Analysis of grab samples showed the lake bottom sediment to be composed of mainly silt and clay, with small but measurable quantities of ice-rafted debris. Surge-generated lake-floor deposits exposed on the surface of the uplifted

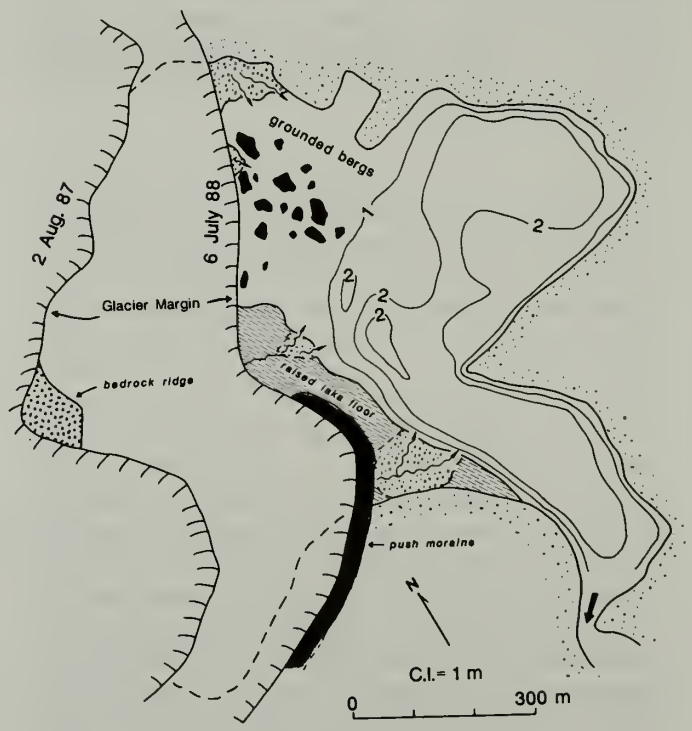

Fig. 4. Lake outline and bathymetry on July 6, 1988. Depth is much reduced from 1987 (c.f. Fig. 2), and areas bordering the glacier are either exposed or nearly so.

pressure/push ridge were massive (unlaminated) and composed of predominantly silt and clay. Exposed deposits were up to 50 cm thick but were undoubtedly much thicker in some parts of the lake basin.

The Lake in 1988

We observed the lake intermittently between June 25 and August 28, 1988. By July 6, only about 25% of the former lake area had remained uncovered by the advancing terminus (Fig. 1). A well-developed push moraine was present along the southwestern edge, and abundant debris-flow material was shed northeastwardly into the lake basin.

The most striking change from 1987, in addition to the greatly reduced lake area, was the major reduction in water depth. Acoustic profiling on July 6 indicated no depth greater than 2.5 m, and large areas of the lake floor near the glacier margin were raised above the lake surface (Fig. 4). Markers near the outlet indicated that the lake surface elevation was essentially at the same level as the previous year; i.e., the lake had not merely drained by lowering of the outlet. The entire northern portion of the basin was less than 1 m deep and cluttered with large grounded icebergs.

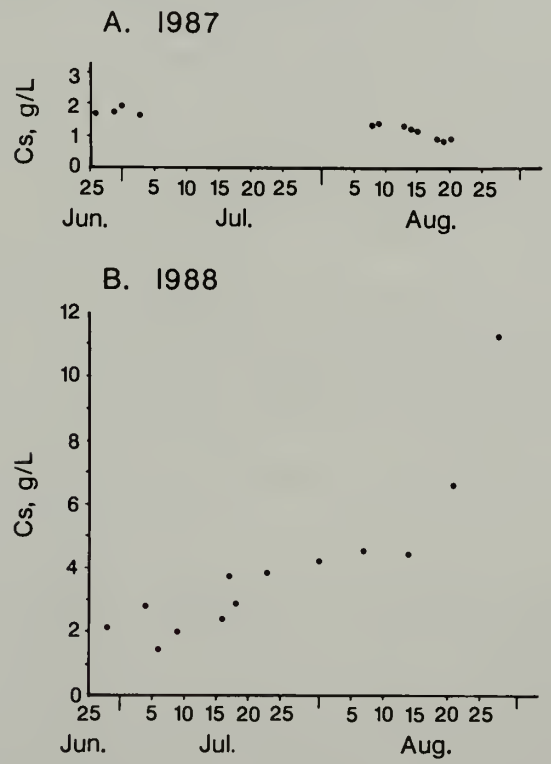

Fig. 5. Suspended sediment concentrations in depth-integrated water samples collected at the lake outlet. Generally decreasing 1987 concentrations reflect slowing of advance through July and August (Fig. 1). Rapidly increasing 1988 concentrations reflect uplifting and fluvial erosion of lake floor.

Successive observations through July and August indicated clearly that the lake basin was being slowly uplifted by the weight of the glacier, much as suggested on a smaller scale by the pressure ridge in 1987. By mid-July, the field of grounded bergs shown in Fig. 4 had become completely exposed, and several days later, small mud islands a few meters in diameter began to appear in remaining portions of the lake. One surveyed berg, approximately 10 m in diameter and standing 3 m above the exposed lake bed, slid 150 m eastward over a 16-day period in response to tilting of the lake floor away from the glacier. By the end of July, the lake was virtually unnavigable by small rubber boats except in the outlet arm. The lake floor had become a mudflat dissected by several meltwater streams.

Suspended sediment concentrations in water samples collected at the lake outlet during both summers record the changing supply of fine sediment produced by the surge event (Fig. 5). From late June through August 1987, the advance was slowing and at the same time producing progressively lower amounts of suspended sediment as the ice moved across the lake basin. This decrease in sediment supply is shown in a roughly two-fold decrease in suspended sediment concentrations over a two-month period (Fig. 5A). In 1988, the progressive increase in suspended sediment concentration in the outlet (Fig. 5B) reflects the increasing proportions of uplifted lake floor, exposing the fine lake-bottom sediment to erosion by meltwater channels. The last outlet sample collected in 1987 (Aug. 28) yielded a very high concentration of 11.3 g/L, representing the condition of near-complete exposure of the muddy lake floor.

Summary and Discussion

The surge of Carroll Glacier at the head of Wachusett Inlet covered over 1 km between June 9, 1987 and July 6, 1988, and the terminus was continuing to advance slowly when these observations were completed. The effects of the advancing ice on the proglacial lake, isolated a few years earlier from the fjord by outwash fans, were dramatic. Lake-bottom topography became initially smoothed over by rapid sedimentation, probably brought on by combinations of suspended fallout and sediment gravity flows. Suspended sediment concentrations in the lake water reached remarkable values of over 9 g/L, which is one or two orders of magnitude higher than values normally reported for glacial lakes. A variably thick layer of massive silty clay was deposited on the lake floor, locally containing ice-rafted debris. This layer was well exposed in a push ridge at the ice margin and also recovered in bottom samples. The remaining lake basin was gradually uplifted by the weight of the glacier in 1988, and

by the end of August, the muddy lake floor was almost completely exposed.

This study is believed to comprise possibly the first set of direct observations of the effects of surging on an ice-margin lake. Such proglacial lakes are commonly associated with glaciers of all scales, and their deposits abound in the geologic record. The role of surging in past glaciations is debatable and largely unknown, although it seems probable that such events were reasonably common. Evidence of such surges in sedimentary deposits, however, has been elusive, and it is hoped that the observations briefly described here may provide some insights for their recognition in the older geologic record.

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Advance of Glacial Tidewater Fronts in Glacier Bay, Alaska

by

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Abstract

Tidewater fronts of glaciers being fed from the Fairweather Range have been advancing for the past several decades into the "west arm" of Glacier Bay. The West Arm trunk glacier historically retreated much more rapidly than did Muir Glacier to the east, which is still retreating. These discrepancies are commonly explained by attributing rate of retreat to a water depth control as the west arm fjord is deeper than Muir Inlet. Furthermore, present glaciers are advancing in the west arm because they have altitude accumulation areas; those of Muir Inlet are of lower altitude and are in the precipitation shadow of the Fairweather Range.

Advance rates are two orders of magnitude slower than retreat rates and appear to be related to how rapidly sediment accumulates in ice-contact with a tidewater front. Sediment build-ups provide terminus stability by decreasing water depth in which the front ends.

Consequently, rates of glacial advance may be a function of sediment yield (determined by drainage area and rates of glacial erosion/transport and debris release), total volume required for sediment build-ups (determined by fjord width, fjord depth less the maximum water depth for frontal stability, and angle of repose of sediment making the build-up), and sediment dispersal patterns (determined by process of debris release and dispersion, type of sediment, and marine currents).

Quantifying these functions will indicate probable advance rates of tidewater fronts in Glacier Bay. These advances may occur to some degree independent of climatic change because previous retreat was a function of water depth and was independent of climatic change after it caused the initial instability at maximum glacial advance.

Glaciers that retreated and constructed ice-contact, proglacial deltas can advance behind those deltas. Others may advance behind submarine sediment accumulations of morainal banks and marine outwash. Hanging glaciers cannot advance until the trunk glacier reaches them because water depth is much greater than sediment yield from their small drainage basins. These hanging glaciers, as indeed all glaciers in the bay, cannot advance by floating because the temperate ice has low tensile strength.

KEY WORDS: Temperate glaciers, tidewater fronts, sediment yields, calving rates, advance rates, retreat rates.

The retreat of tidewater termini in Glacier Bay National Park and Preserve (GBNPP), southeastern Alaska, has been well documented by several workers (e.g., Field 1979) and summarized by Powell (1980). After reaching a position of maximum retreat, some tidewater fronts have been advancing. This asynchroneity of termini movements has been noted in the past and been attributed to: (1) frontal stability occurring by the glacier profile changing to decrease the size of the ablation area (Mercer 1961; Post 1975; Mayo 1988), (2) increased precipitation at high altitude following a rise in the equilibrium line altitude (ELA) (compare Field 1947, 1979; Mercer 1961; Goldthwait et al. 1963), and (3) accumulation of sediment build-ups at the grounding line that decrease water depth and increase frontal stability (Goldthwait et al. 1963; Post 1975; Powell 1984; Mayo 1988). These types of non-climatic responses have also been noted for Pleistocene ice sheets (e.g., Mercer 1968; Hillaire-Marcel et al. 1981; Mann 1986). The aim of this paper is to review evidence for movement of tidewater fronts in GBNPP and evaluate the influence on those movements of sediment build-ups at grounding lines.

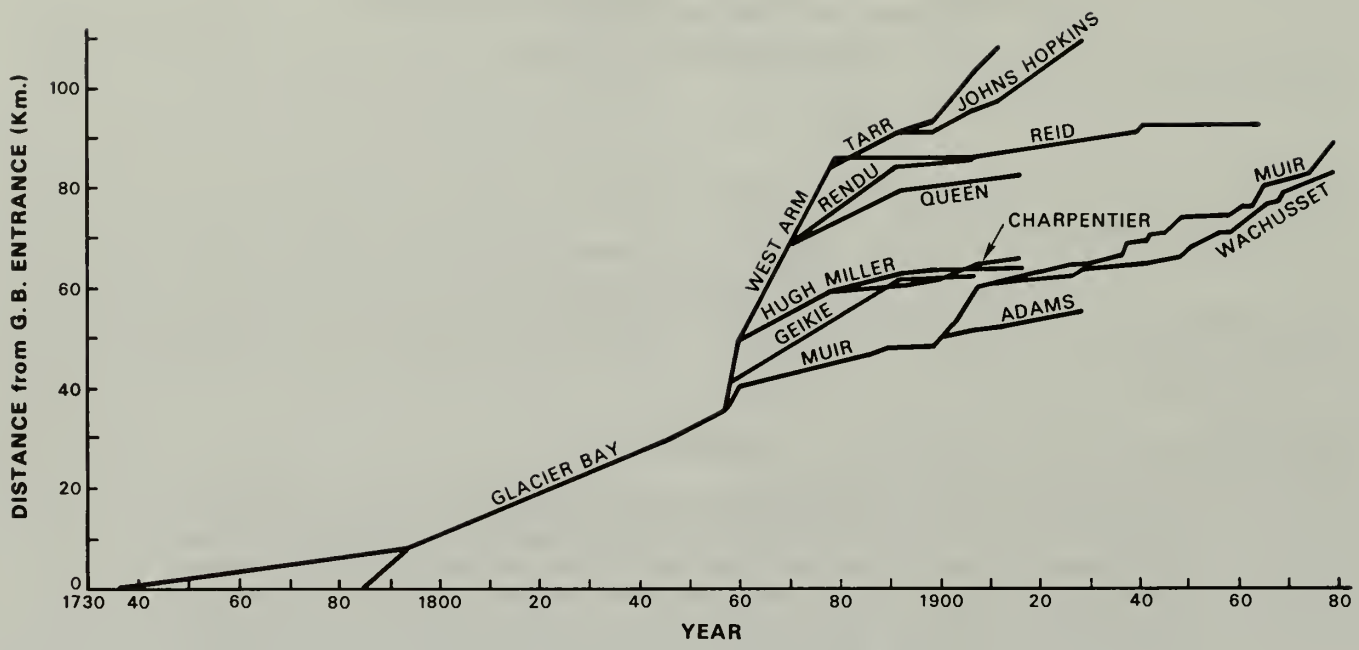

Fig. 1. Distance on a given year of tidewater fronts from the entrance of Glacier Bay. Slope of lines represents rate of retreat.

Table 1. Rates of movement of tidewater termini of temperate valley glaciers in Glacier Bay, Alaska.

	FJORD	PERIOD	RATE (km/yr)
Advance	Yakutat Bay	1895-1986	0.02
	Crillon Inlet	1926-1961	0.02
	Johns Hopkins Inlet	1929-1979	0.05
	Tarr Inlet	1942-1979	0.04
	Reid Inlet	1964-1979	0.04
Retreat	Glacier Bay	1857-1860	4.83
		1860-1879	1.84
	Tarr Inlet	1899-1907	1.30
	Muir Inlet	1857-1860	1.80
		1903-1907	2.00
		1936-1937	2.40
		1963-1964	1.60
		1964-1965	2.00
		1978-1979	2.10
	Wachusett Inlet	1968-1969	1.50

Effects and Rates of Movement of Tidewater Fronts

Since the Neoglacial advance, glaciers of GBNPP have retreated relatively rapidly (Fig. 1). Subsequently, after the termini reached a position of maximum retreat, many started to advance. The rates of advance are about two orders of magnitude slower than averaged retreat rates (Table 1).

Rates of retreat were controlled primarily by water depth (Fig. 2). For example, the west arm trunk glacier between 1860 and 1879 ended in the deepest water any retreating terminus encountered in the bay, and there it experienced the most rapid retreat. Although other variables have influences on frontal movement on short time scales of a year or two (Powell 1983, 1984), water depths are a primary control on terminus stability (Brown et al. 1982). A terminus can be quasi-stable in shallow water and may become stable at such sites if ice flux through the glacier is greater than the speed of calving. Calving speed increases dramatically in deep water and most often exceeds ice flux to the terminus, and retreat rates are then much faster.

If terminus stability is reached, then the glacier can readvance. Initiation of stability during a glacial retreat phase commonly occurs at a pinning point, such as a sill on the fjord floor or perhaps a constriction in or narrowing of valley walls (e.g., Field 1947; Mercer 1961). The pinning point forces calving speed and ice flux to approach equilibrium. Without the pinning point, retreat may continue until the ablation area has been decreased sufficiently and equilibrium is reached. However, in deep water, calving speed may not allow equilibrium even then.

The profiles of these marine-ending glaciers are commonly concave-up with a low surface slope, and any rise in the equilibrium line can rapidly increase the area of surface ablation (Fig. 2; Mercer 1961). Surface melting and down wasting then adds to calving and increases ablation rates so that the glacier is not in equilibrium. Typically, to maintain equilibrium, such a glacier has 60 to 70% of its surface within its accumulation area (Meier and Post 1962). Surface slope may steepen close to the terminus, especially during rapid frontal retreat (Brown et al. 1982), but not until most of the surface slope steepens (such as the Grand Pacific profile in Fig. 2) does the retreat slow. The terminus may reach quasi-stability once the surface ablation area has decreased and the glacier can thicken, with the result that the terminus may advance. If depths are shallow, the advance can occur without any subsequent change in the ELA because the glacial profile is thicker than during retreat. The advance will be limited, since eventually the surface ablation area will increase and equilibrium will be reached.

Added to profile changes, an increase in precipitation at high altitude can increase stability (Goldthwait et al. 1963). In Glacier Bay, outer coast and west arm glaciers are fed from high altitude accumulation areas in the Fairweather Range and receive the full effect of orographic precipitation from the Gulf of Alaska. Indeed, since Neoglacial retreat, precipitation on the Fairweather Range has probably increased (e.g., Mercer 1961) and assisted the advance of outer coast and west arm glaciers. Glaciers in Muir Inlet are fed from lower altitude accumulation areas that are thought to be in the precipitation shadow of the Fairweather Range. This contrast provides an excellent example of non-climatic forcing of terminus fluctuations of marine-ending glaciers.

The glaciers of Muir Inlet, which are less favored by precipitation, experienced a slower retreat than those more favored glaciers being fed from the Fairweather Range. That contrast is attributed to deeper water in the west arm in which

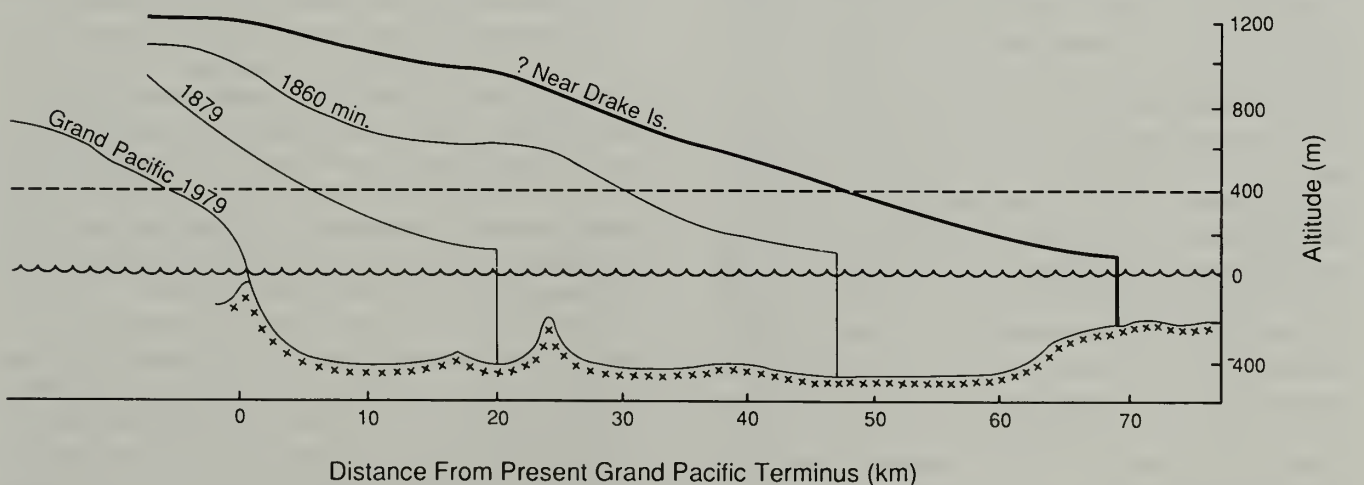

Fig. 2. A series of longitudinal surface profiles and assumed bed profiles (from seismic reflection) of the west arm of Glacier Bay since glacial retreat from near Tlingit Point. The dashed line is an equilibrium line at 400 m altitude, and surface area of the glacier below that line changes during retreat without moving the ELA. Profiles based on Brown et al. (1982).

the Fairweather Range glaciers ended. Furthermore, precipitation is not the sole cause of readvance, although increased precipitation in the Fairweather Range would have helped. However, readvances have not been synchronous, and although less favored by precipitation, glaciers in Muir Inlet (e.g., Riggs Glacier) have recently started to readvance after reaching equilibrium at maximum retreat.

Inherent in this change from retreat to readvance, as well as controlling the rate of advance, is sediment yield from the glacier. Sediment build-ups at a grounding line decrease water depth which decreases calving speed, and consequently, terminus stability is enhanced, and it may even advance.

Sediment Yields and Grounding Line Build-ups

Potential sediment yields to the sea from glaciated basins increase with the size of the basin as a glacier expands under the following conditions: (1) uniform subglacial sediment/rock types, (2) constant subglacial debris conditions (erosion-transport-release) during expansion, and (3) minimal sediment storage (probably true except for glacial minimum conditions where extensive land areas are exposed in a drainage basin).

The general concept can be tested in reverse by evaluating the decreased sediment yield during retreat of Muir Glacier from 1899 to 1980 (Fig. 3). For this example, most other variables have probably been as constant as one may expect in a natural system. Total sediment accumulated during retreat of Muir Glacier can be determined from seismic profiles (Molnia et al. 1984). Sediment volumes in successive basins up Muir Inlet were calculated using an average thickness and area of each basin. Those volumes produced per ice-contact year were determined using the well-documented terminus positions as controls for the successive time periods. The result is numbers for the average sediment yield to a basin while Muir Glacier terminus was within and at the head of that basin. For each position of the terminus at a basin head, the area of Muir Glacier was calculated using reconstructed drainage basins through time (Brown et al. 1982). The procedure assumes that fjord floor sediment basins are closed systems, which they are not. However, most sediment delivered to the sea by a tidewater front accumulates in the immediate ice-contact basin (Powell 1981, 1983; Cowan 1988). Sediment lost to the system and side inputs contributing sediment after retreat are taken as constant over time so that if there is an error in estimating sediment volume, it is constant among basins.

A reasonable logarithmic decrease in sediment yield with decreasing drainage basin area was produced (Fig. 3). Two

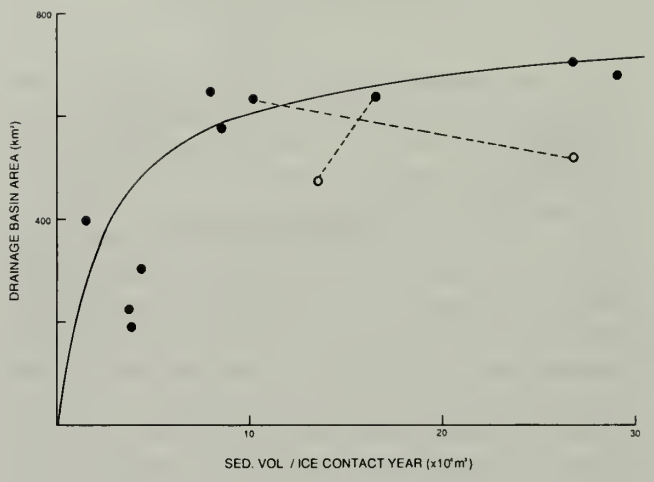

Fig. 3. Sediment volume in ice-proximal basins estimated from seismic profiles (from Molnia et al. 1984) averaged over the period of time Muir Glacier remained in or at the head of each basin, plotted against the successive areas of Muir Glacier's drainage basin (determined from Brown et al. 1982). The plot shows the relationship during recent retreat of the glacier.

points fall off the trend by having more sediment than would be predicted from the drainage area of Muir Glacier at the time. They are areas where Muir Inlet continued to receive sediment from the tributary McBride Glacier after Muir Glacier had retreated. Interestingly, when the appropriate drainage area and sediment yield of McBride is added to those points, they plot on the curve.

Some rates of accumulation of build-ups at grounding lines are presented in Table 2. These figures are independent of water depth, and size of drainage basin is not considered. On average, 8.8×10^6 m³/year of sediment accumulates at grounding lines of these temperate valley glaciers in Glacier Bay. Whether that volume of sediment can contribute to glacial advance then depends on: (1) the movement of the terminus, (2) the critical height of the grounding-line build-up (water depth at the terminus minus the critical water depth for stability), and (3) the type of build-up (its geometry and processes of sediment release and dispersion).

Firstly, movement of the terminus is important because unless it is at least quasi-stable, the sediment is deposited in a sheet as the terminus moves, rather than accumulating as a build-up (Powell 1981; Powell and Molnia 1989).

The second variable for stability, critical water depth, controls the calving speed. Water depth is decreased by sediment build-ups whose heights are a function of sediment yield and angle of repose of the sediment.

Table 2. Sediment yields for deltas and grounding-line build-ups in Glacier Bay. Some background data was used from Field (1947), Goldthwait et al. (1963), McKenzie (1986), Cowan (1988), and Seramur (1988).

FEATURE	PERIOD	AGGRADATION (m/year)	PROGRADATION (m/year)	SEDIMENT YIELD (m^3/year)
Adams River Delta	1948-1977	0.4	20	$6.8x10^5$
Carroll Glacier Delta (Queen)	1920-1948	3.0	57	$2.8x10^7$
Carroll Glacier Delta (Wachusett)	1980-1984	9.0	590	$4.1x10^7$
Crillon Glacier Delta	1926-1961	3.0	17	$1.6x10^6$
Rendu Glacier Delta	1892-1964	2.5	14	$2.6x10^4$
Riggs Glacier Delta	1979-1985	13.0	43	$2.8x10^6$
Seal River Delta	1948-1977	0.7	66	?
McBride Glacier Morainal Bank	1978-1981	-	-	$4.0x10^5$
McBride Glacier Ice-contact	1985-1987	-	-	$2.0x10^6$
Muir Glacier Push-morainal Banks	1965-1974	-	-	$2.7x10^6$

Thirdly, the main types of build-ups are morainal banks that include grounding-line fans and ice-contact deltas. Morainal banks are produced at grounding lines by meltout of glacial debris, dumping of supraglacial debris during iceberg calving, subglacial meltout and lodgement, and subglacial squeeze and push. By far the largest contributions are grounding-line fans built by subglacial streams discharging at the sea floor. These forms have been observed to aggrade to sea level to eventually form ice-contact deltas; e.g., at Lamplugh, McBride, and Riggs Glaciers. Major aggradation requires continuous terminus stability for several to tens of years. Ice-contact deltas can also form by marginal streams when the terminus is nearly leaving the sea. The deltas prograde down fjord, but importantly, they prograde across the terminus to decrease water depth at the grounding line.

Because of high sedimentation rates, steep slopes, and glacial movement, sediment redeposition from these build-ups is common. The process by which mass movement occurs is important for frontal stability. If sediment is transported far away from the grounding line such as in turbidity currents, then volume of the build-up decreases. In fact, a mass failure of sediment from the build-up, such as may be induced by an earthquake, could cause a glacial retreat by removing the pinning-point and increasing water depth.

Redeposition by slides/slumps does not move sediment as far from the build-up as turbidity currents, so their effect of reducing the volume of build-up is less. In fact, slide/slump deposits can help to maintain the build-up by maintaining its frontal slope, which is true unless a massive failure occurs.

Summary

Climate is a first-order control on fluctuations of tidewater fronts. However, because of the conditions required for stability of termini of marine-ending glaciers, other factors

that affect water depth, such as eustacy, isostacy, and sediment yield are important second-order controls. In Glacier Bay today, eustacy and isostacy have no effect on termini stabilities, and data presented here shows that sediment yield has allowed glacial advance that can be independent of climatic effects. The advance rates are two orders of magnitude slower than retreat rates, probably because of the time required to accumulate sediment in grounding line build-ups. Such advances will be limited in extent until a positive climatic forcing enhances the mass balance.

Hanging glaciers cannot advance until the trunk glacier reaches them because water depth is much greater than sediment yield from small drainage basins. These hanging glaciers, as indeed all glaciers in the bay, cannot advance by floating because temperate ice has low tensile strength and calves before it can float.

Surges may not necessarily follow the constraints presented, and their fluctuations are on a much shorter time scale than those discussed. However, all of these termini changes may be important to consider for making future management plans. Where tourists can see tidewater fronts and the extent of habitat area for terrestrial and aquatic communities will depend on future glacier movements. For such predictions, we need more specific information on sediment yields and critical water depths of each glacier and significantly more information on glacial mass balance throughout the bay.

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Movements and Habitat Use of Dungeness Crabs and the Glacier Bay Fishery

by

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Abstract

To determine short-term patterns of movement and habitat use by Dungeness crabs, *Cancer magister*, in southeastern Alaska, we attached ultrasonic tags to 16 males, 8 nonovigerous females and 11 ovigerous crabs in five bays in southeastern Alaska. The positions of the crabs were fixed at six-hour intervals for about a week.

Our results indicate that the tagged crabs were active about half of the time. Males were 1.7 to 3.7 times more active than ovigerous crabs but did not differ from nonovigerous females in activity. When active, males moved further per unit time ($\bar{y}$ = 7.7 m/h) than did females ($\bar{y}$ = 1.6 m/h). Ovigerous and nonovigerous females moved at about the same rate. Males visited a greater proportion ($\bar{y}$ = 42%) of the habitats available to them than did ovigerous crabs which visited only 27% of the available habitats. No significant difference was detected in the proportion of available habitats visited by males compared to nonovigerous females. The data indicate that female Dungeness crabs spend more time in a particular habitat and move at slower rates than males and that ovigerous crabs are less active and visit fewer habitats available to them than males. This may affect the relative probability of encountering a crab pot between ovigerous female and male Dungeness crabs.

KEY WORDS: *Cancer magister*, biotelemetry, habitat use, crab fishery, short-term movements, activity.

The Dungeness crab, *Cancer magister* Dana 1852, is one of the marine species subject to increasing commercial exploitation in Glacier Bay National Park (Taylor and Perry, this volume). Most commercial fisheries in the Park are currently managed by the Alaska Department of Fish and Game. Although the National Park Service does not currently impose special restrictions on the Dungeness crab fishery in Glacier Bay, managers may in the future choose to invoke restrictions if the fishery continues to expand.

As elsewhere in Alaska, the Dungeness crab fishery in Glacier Bay National Park harvests males only. Fishery managers are concerned that nontarget individuals incidentally caught in the fishery may suffer increased mortality as a result of the stress of handling prior to release (Tegelberg 1972, Barry 1984). Do harvestable male crabs differ from nontarget individuals in their susceptibility to capture by the fishery? Capture vulnerability may depend, in part, on behavioral differences among classes of individuals in the crab population. Here we report the results of a study using biotelemetry to examine differences in activity levels, rates of movement and habitat use between sexes and between reproductive states of female Dungeness crabs.

Methods

Dungeness crabs were hand-collected by divers at two locations (Bartlett Cove and the Beardslee Islands) in Glacier Bay National Park and at three locations elsewhere in southeastern Alaska (Fig. 1, Table 1). Carapace width (anterior to the tenth lateral spine) and weight were recorded for each crab. The ranges in carapace width (CW) were: males, 134-190 mm; females, 132-171 mm. Eighty-one percent of the males in the study were of harvestable size (>165 mm CW; Table 1). An ultrasonic tag (length 37 mm, diameter 9 mm, weight in water 5.7 g) with a battery life of 10-14 d was attached to the

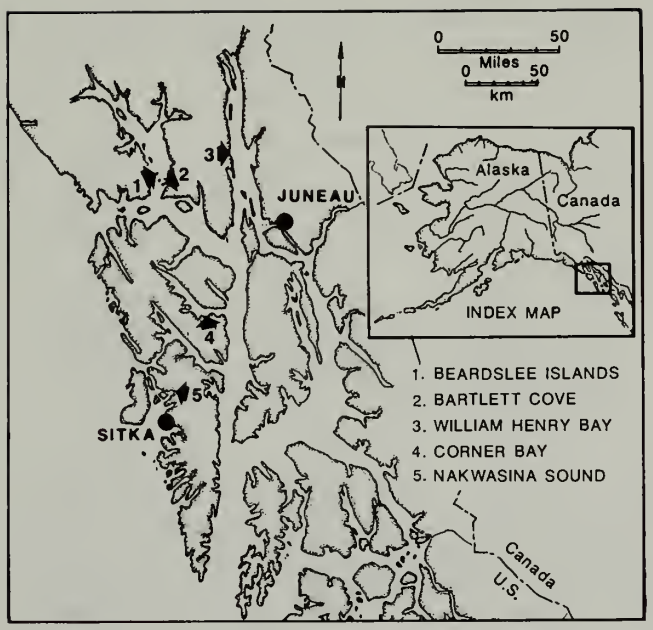

Fig. 1. Location of tagging sites in southeastern Alaska.

right epibranchial region of the carapace of each crab using a non-toxic, "5-minute" marine epoxy. The crabs were then placed in a tank receiving seawater "once-through" from the upper water column near the site where they were captured. Crabs were held in the tanks for a period not exceeding 10 h before being released, usually at the site of capture or in a habitat similar to that where they were captured.

The locations of the crabs were fixed at about six-hour intervals (high and low water) after release using a directional hydrophone and receiver operated from a small boat. We "marked on top" the crab's position and then fixed the position of the boat by triangulation using a hand-held compass to take bearings on at least three targets on shore or by using a sextant as a pelorus. Immediately after release, the tagged crabs often exhibited an accelerated rate of movement which lasted 10 to 43 h depending on the individual. Fixes obtained during this adjustment period or those considered to be inaccurate were discarded, leaving 654 usable fixes of the 844 obtained on the 35 tagged crabs.

Benthic habitats were characterized by divers on the basis of substrate type, bottom slope, depth and dominant biotic cover. Divers delineated habitats by deploying buoys; their positions were fixed using one of the instruments mentioned above.

Two types of errors affected fix accuracy: (1) ultrasonic error and (2) navigational error. Each of these errors comprised a system component and an operator component. We estimated

Table 1. Number of *Cancer magister* fitted with ultrasonic tags at four bays in southeastern Alaska.

Site	Date	Crabs tagged		
		Male	Female	
			O	N[a]
Beardslee Islands (58°32'N, 135°55'W)	7-17 Jun 1988	3 (3)	3	
Bartlett Cove (58°27'N, 135°55'W)	17-24 Feb 1988	3 (1)[b]	4	-[c]
William Henry Bay (58°43'30"N, 135°13'30"W)	14-20 May 1987	2[d] (1)	3	-
	15-22 Oct 1987	3 (2)	1	2
Corner Bay (57°44'20"N, 135°07'30"W)	15-23 Jul 1987	3 (3)	-	3
Nakwasina Sound (57°12'N, 135°24'W)	17-23 Jun 1987	2[d] (3)	-	3

a. O = ovigerous, N = nonovigerous.
b. Legal males (carapace width >165mm) tagged in parentheses.
c. Dash indicates no crabs tagged in this category.
d. Three crabs tagged, but we failed to receive a signal from one tag for an unacceptably long period of time.

Table 2. Statistical tests of differences in behavior between sexes and female reproductive states in *Cancer magister* at four bays in southeastern Alaska. $\overline{X}$ = mean, CI = 95% confidence interval, N = number of tagged crabs, P = probability of using Fisher's LSD procedure following a one-way analysis of variance. The contrast was judged significant if P 0.05.

Behavior	Sex/Reproductive State	$\overline{X}$ ± CI	N	Contrast[a]	P
Activity (%)	Male	59.1 ± 46.0-72.3	16	M X FO	P< 0.05
	Female O[b]	30.1 ± 9.3-51.0	10	M X FN	P> 0.05
	Female N	45.6 + 26.0-65.3	8		
Rate of movement (m/hr)	Male	7.7 ± 4.3-11.1	16	M X FO	P< 0.05
	Female O	1.4 ± 0.2-2.5	10	M X FN	P< 0.05
	Female N	1.9 ± 1.0-2.8	8		
Time in original habitat (%)	Male	31.0 ± 11.9-50.0	16	M X FO	P< 0.05
	Female O	67.0 ± 40.1-93.9	10	M X FN	P< 0.05
	Female N	63.7 ± 31.6-95.9	8		
Habitats visited (%)	Male	42.4 ± 35.5-49.4	16	M X FN	P< 0.05
	Female O	27.2 ± 17.0-37.4	10	M X FN	P> 0.05
	Female N	40.7 ± 24.3-57.1	8		

a. Comparison of means: M, male; FN, nonovigerous female; FO, ovigerous female.
b. O, ovigerous; N, nonovigerous.

the ultrasonic error by marking on top a crab, lowering the anchor of a buoy to the bottom, diving on the crab, and measuring the distance between the crab and the buoy anchor. The ultrasonic error averaged 3.6 m (n = 19, 95% confidence interval =± 1.4 m). The navigational error was estimated by returning to the same position (marked by a buoy) repeatedly under various environmental conditions over the course of a tracking period, obtaining a fix, and then measuring the variability in the plotted positions of the fixes. The average navigational error ranged from 4 to 13.9 m over the sites. The ultrasonic and navigational errors were summed to obtain the fix error. In addition to recording residence time in the habitats where the crabs were released and the number of habitats visited by each crab, we calculated the following behavioral measures:

Activity — a crab was considered active when it exhibited perceptible movement between fixes; i.e., when the distance between two fixes exceeded the sum of the fix errors (ΣEi).

Rate of movement — Rate of movement (R) was calculated by R = (D - ΣEi)/T, where D is the distance (in meters) between fixes and T is the time (in hours) between fixes. ΣEi is defined above.

Analysis of variance was used to test for d between means. Percentage data were transformed with the arcsin transformation to stabilize variances and normalize data distributions. Tests were judged significant if $p < 0.05$.

Results

The 35 crabs fitted with sonic tags that were used in the analyses were active on the average 47% of the time. Mean activity levels of males significantly exceeded those of ovigerous crabs (Table 2), ranging from 1.7 to 3.7 times the activity levels of the ovigerous crabs during three of the four study periods when both groups were tagged. During the fourth period (October 1987 at William Henry Bay), only one ovigerous crab was tagged (Table 1). The activity levels of nonovigerous females did not differ from those of the males (Table 2).

When active, males tended to move greater distances per unit time than did females (Fig. 2, Table 2). Rates of movement of males exceeded those of nonovigerous females by 4.0 times and those of ovigerous crabs by 5.5 times.

Males spend proportionately less time (31%) in the original habitat in which they were captured and released than did females (66%). This relationship held regardless of whether the females were brooding eggs or not (Table 2).

Males visited a larger percentage of the habitats available to them than did ovigerous crabs (Table 2). (We define habitats available to *Cancer magister* in a bay as those in which at least one *C. magister* was found over the course of a tracking period.) Nonovigerous females visited the same percentage of available habitats as did males (Table 2).

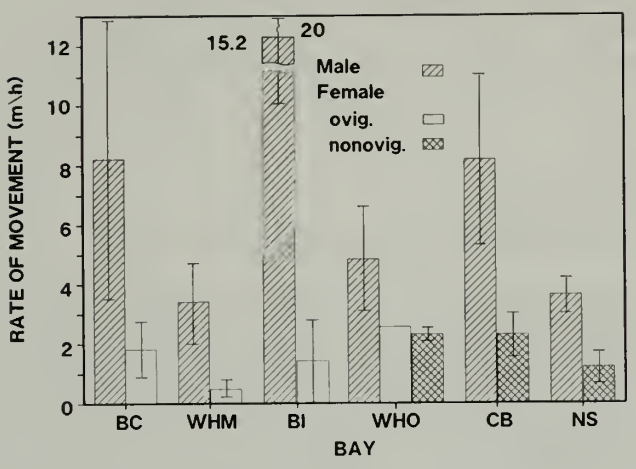

Fig. 2. Rates of movement of tagged *Cancer magister* at four bays in southeastern Alaska. Error bars are one standard error either side of the mean. Abbreviations are: BC, Bartlett Cove; WHM, William Henry Bay, May 1987; BI, Beardslee Islands; WHO, William Henry Bay, October 1987; CB, Corner Bay; NS, Nakwasina Sound.

Discussion

Our results indicate that in southeastern Alaska, female *Cancer magister,* whether brooding eggs or not, do not move as readily between habitats as male crabs and exhibit reduced rates of movement compared to males. In addition, ovigerous *C. magister* tend to be less active and visit fewer of the habitats available to the population as a whole than do male crabs. These results are supported by our diving observations of ovigerous crabs at 11 localities in southeastern Alaska over the past six years which indicate that ovigerous *C. magister* tend to aggregate in discrete areas. Often these areas are characterized by sediments consisting mostly of coarse sand, presumably with enhanced interstitial water flow, and therefore a favorable environment for the crabs to brood their eggs.

Our results contrast in two respects with work on other species of crabs. Hazlett and Rittschof (1975) found that although female *Mithrax spinosissimus,* a large spider crab, tended to move less frequently than males, when males and females moved, they moved the same distance. In our study, the frequency of movement of females depended on whether or not they were ovigerous, but when crabs moved, males moved a greater distance per unit time than females. Edwards' (1958) results on the movements of the shore crab *Carcinus maenas* were similar to those of Hazlett and Rittschof (1975) on *M. spinosissimus* with respect to the frequency of movement of males versus females; he did not compare distances moved. We know of no study comparing movements of ovigerous crabs with males or nonovigerous females.

Although studies of the effects of handling by commercial fishermen on nontarget individuals have focused on softshell crabs (Tegelberg 1972, Barry 1984), effects on ovigerous females and the developing embryos in their broods during the colder months also concern managers. The effects of subfreezing air temperatures on crabs brought to the surface, held there for various periods of time and then returned to the water, have not been adequately studied. However, our results indicate that ovigerous *C. magister* are more restricted in their movements than males and therefore perhaps would be less likely to encounter a crab pot than males. In addition, fishermen generally place their pots in habitats at greater depths than those we have observed and may move the pots if females begin to constitute a large portion of the catch. The tendency of ovigerous *C. magister* to restrict their movements, often in shallower habitats, compared to male crabs would further reduce the vulnerability of ovigerous crabs to the fishery.

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Commercial Fishing Patterns in Glacier Bay National Park, Alaska

by

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Abstract

Commercial fishing has been an established industry in Glacier Bay since the 1880s. The industry remains strong today in park waters without statutory or regulatory authorization. The majority of the harvest from the park is taken from the outer coast waters, but the take of Dungeness crab has been growing steadily within the Bay over the last five years. In 1987, fishermen harvested 2.7 million pounds of salmon, halibut, Dungeness crab, tanner crab, king crab and shrimp. The ex-vessel value was about $4 million, the processed value was about $8 million and the general regional value was estimated to be $12 million. Despite the economic importance of the industry, biological resource impacts and user conflicts in the national park need to be addressed.

KEY WORDS: Commercial fishing, resource management, Glacier Bay, Alaska, national parks.

Commercial fishing activities extract millions of pounds of biomass annually from Glacier Bay National Park. In 1984 and 1987, as seasonal National Park Service (NPS) Resource Management Biological Technicians, we observed commercial fishing operations, interviewed fishermen, reviewed historic data in park files and obtained catch statistics from the managing agencies. Our purpose was to assess the impact of commercial fishing on park resources and evaluate conflicts with Park Service goals and philosophies.

Glacier Bay National Park has a long history of commercial fishing. La Perouse observed a Tlingit Indian fish camp in Lituya Bay in 1786. A saltery operated in Bartlett Cove from about 1885 into the 1890s. The Dundas Bay Cannery began packing fish in 1890. The cannery operated several small vessels, gill nets, seines and fish traps. Fish were caught from lower Glacier Bay, Icy Strait and from points outside the present park boundaries. At that time, a run of 75-100 thousand sockeye salmon (*Oncorhynchus nerka*) occurred into the Bartlett River and Bartlett Lake. A significant number were also taken from Berg Bay. The Bartlett River sockeye run ended at the turn of the century when seismic activity caused the lake's outflow to become subsurface. Hoonah Tlingits and some early Gustavus residents in the 1920s trolled for salmon commercially in Glacier Bay.

Bruce Black, a Park Ranger in the 1950s, recorded active salmon trolling on the outer coast and within Glacier Bay to Geikie Inlet. Purse seining was conducted in North Indian Pass and Excursion Inlet. A fish buyer operated in Dixon Harbor, and many vessels anchored there and at Graves Harbor, Black reported.

Species and Fishing Methods

In this decade, the waters of Glacier Bay National Park have supported fisheries for king crab (*Paralithodes* sp.), Dungeness crab (*Cancer magister*), Tanner crab (*Chionoecetes bairdi*), shrimp (*Panadalus* sp.), Pacific halibut (*Hippoglossis stenolepis*), and five species of salmon (*Oncorhynchus* spp.). The king crab fishery has become severely depressed throughout Southeast Alaska in recent years, and the shrimp fishery in Lituya Bay has always been small. The other fisheries are

currently thriving. Fish and shellfish are taken by power and hand trolling, purse seine (Excursion Inlet only), long line, jigging and pots. Some trawling occurred within Glacier Bay in the early 1980s. It is now banned there but may still occur on the outer coast.

Legal and Management Aspects

The International Pacific Halibut Commission (IPHC) manages the halibut fishery through quotas and limited openings. There is no limited entry permit system for halibut. The Commercial Fish Division of the Alaska Department of Fish and Game (ADF&G) manages all the other fisheries by a system of quotas, gear restrictions, limited openings and limited entry permits.

Commercial fishing is authorized by the Alaska National Interest Lands Conservation Act of 1980 (ANILCA) for Glacier Bay National Preserve, but no statutory authorization exists for the National Park. ANILCA and the Wilderness Act both prohibit commercial fishing in wilderness. National Park Service 1984 regulations [36 CFR 2.3 (4)] closed all park areas nationally to commercial fishing except where authorized by federal statute. The NPS has never acted to enforce the regulation in Glacier Bay National Park. The park's General Management Plan recommends that traditional commercial fishing activities be allowed to continue but that no new fisheries be allowed to develop. The Park Service has banned commercial fishing within Glacier Bay (but not for Icy Strait or the outer coast) for humpback whale prey species. Fishing vessels must abide by speed and course restrictions established for all vessels in areas used by whales, but they are not limited in number, nor are they required to have entry permits as are private and concession vessels. In 1983, the NPS prepared regulations to ban commercial fishing within wilderness waters, but the final regulations never cleared the Secretary of the Interior's office. The uncertainty serves no one well.

Catch Statistics for Glacier Bay National Park

Fishery management agencies require fishermen to report the location of their harvest on fish sales tickets. The tickets are compiled by the agencies to determine the catch of each species in each reporting area. The reporting areas do not align with the boundaries of Glacier Bay National Park. Therefore, the portion of catch taken within the park's waters must be estimated.

The IPHC estimated that 25% of the halibut harvest in Statistical Area 182 of Regulatory Area 2C is taken from within Glacier Bay and 10% is taken from park waters in Icy Strait. Approximately 0.3% of the catch in Regulatory Area 3C originates from park waters along the outer coast.

ADF&G salmon statistical reporting areas are shown in Fig. 1. All of Area 116-05 is located in the three-mile-wide strip of park waters. A portion of catch from adjacent areas is reported within 116-05. ADF&G suggests that 90% of the 116-05 catch should be assigned to park waters. A small portion of Area 181 is within the park boundary, but the catch from there is not considered in this analysis. Observations of vessels and discussions with fishermen and ADF&G personnel suggested that about 15% of the Area 114 troll harvest is from park waters. Fifty percent of the Excursion Inlet purse seine harvest is assumed to be from park waters.

ADF&G Shellfish Statistical Areas are shown in Fig. 2. The entire catch of Statistical Areas 116-11 through 116-14 is taken from park waters. The Area 181 catch was not used. The total harvest of Areas 114-70 through 114-77 was estimated to be taken from within Glacier Bay. Fifty percent of the harvest from Areas 114-21 and 114-23 was assumed from park waters because about half the zone's shallow habitats are there. Half the Excursion Inlet, Area 114-80, catch was estimated to come from within the park. All of the harvest for Area 114-60 was assigned to Dundas Bay.

There are problems with these estimations. Fishermen do not always report correctly. They may lump catches from several areas on the fish tickets. In 1984, there were 155 commercial pots from three different crab for area 114-60. The

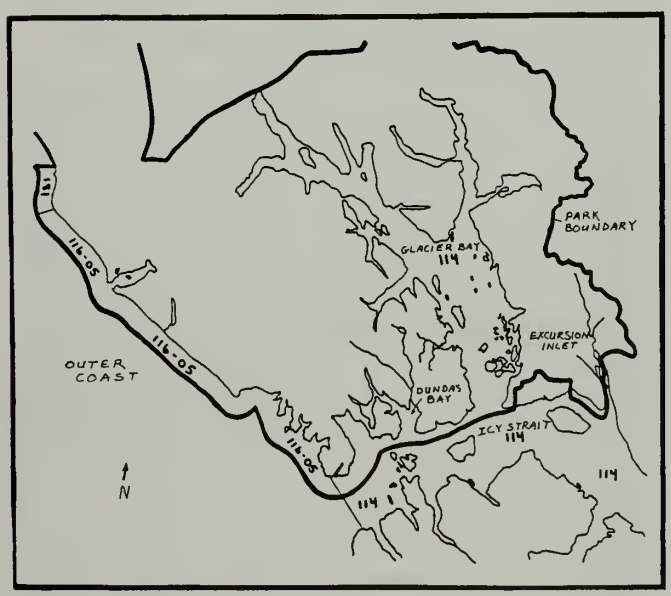

Fig. 1. ADF&G troll statistical areas encompassing Glacier Bay National Park.

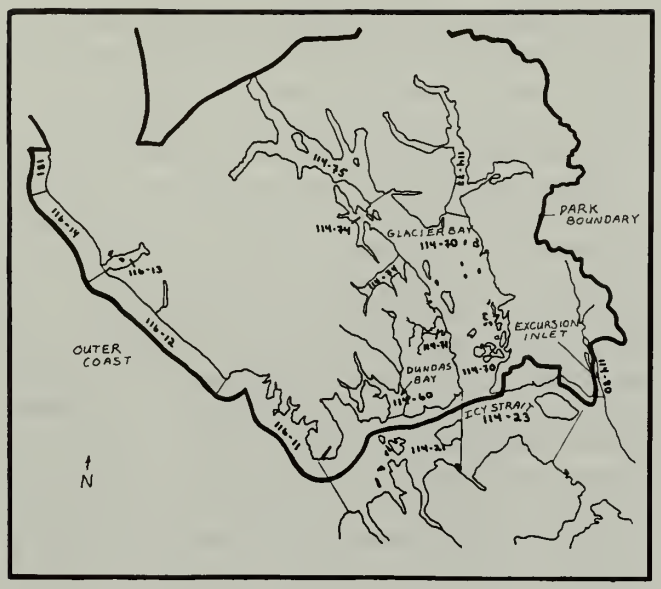

Fig. 2. ADF&G Shellfish Statistical Areas encompassing Glacier Bay National Park.

estimations of percentage catch within park waters may be incorrect, due to variations according to species, season or year. ADF&G provides no confidence ranges on their figures. The IPHC estimate is only their best estimate based on a few vessel logs.

The Glacier Bay National Park Commercial Fish Harvest

ADF&G catch statistics for 1983-1987 were calculated from printouts provided in September 1988. Table 1 presents the estimated troll salmon harvest for those portions of ADF&G statistical areas within park waters for the years 1983-1987, in thousands of pounds of fish. Coho salmon (*Oncorhynchus kisutch*) is the most important species (67% in 1987), followed by chinook (*O. tshawytscha*). The outer coast is the most important area, with 73% of the 1987 park salmon catch.

Table 2 presents the estimated purse seine salmon take for the half of Excursion Inlet within park waters, for the years 1983-1987. This fishery targets the fall chum salmon run. Other species caught are incidental. The total 1987 park salmon catch was estimated to be 1.22 million pounds.

Table 3 presents the estimated halibut harvest for 1983-1987. The halibut catch from park waters has averaged approximately 500,000 pounds per year. Vessels counted and mapped daily from the air during the halibut openings in 1984 and 1987 indicated numbers have varied widely from day to day and from year to year. Most of the halibut effort within the park has been within Glacier Bay and in Icy Strait from Pt. Carolus to Cape Spencer. In 1984, an average of 78 vessels were sighted per day in the inside waters. In 1987, the average was 40 vessels.

Table 1. Troll salmon harvest for GBNP waters. Catches in thousands of pounds of fish.

Glacier Bay and Icy Strait (15% of Area 114 harvest)					
Species	1983	1984	1985	1986	1987
Chinook	40	51	37	16	21
Coho	130	145	146	77	83
Pink	53	46	186	5	88
Sockeye	2	3	3	0	3
Chum	5	7	11	3	3
Totals	230	252	383	101	198
Outer Coast (90% of Area 116 harvest)					
Species	1983	1984	1985	1986	1987
Chinook	228	116	136	119	97
Coho	1098	583	871	461	417
Pink	42	28	102	5	24
Sockeye	5	3	3	1	5
Chum	15	4	14	6	4
Totals	1388	734	1126	592	547
Park-wide Totals	1618	986	1509	693	745

Table 4 presents the Dungeness crab harvest by park area for 1983-1987. In 1983, 75% of the crab was harvested from the outer coast, but in 1987, the portion was 47%. The primary coastal effort is north of Lituya Bay. The crab harvest has steadily increased in Glacier Bay and accounted for 43% of the catch in 1987, 4.5 times the catch of 1983.

The Beardslee Islands represent the most important commercial crabbing area within Glacier Bay. Pots are found in every shallow embayment throughout the wilderness waters, usually set less than 20 m deep and 30 m apart in strings allowing systematic service. There are often parallel strings for several crabbers in each bight. Crabbers pull the pots with a power winch, typically every three to five days. Crab vessels vary from large aluminum skiffs with one- or two-person crews to 50 ft boats. Outer coast crab vessels are larger due to rough seas.

Table 5 presents harvest data for king crab, tanner crab and shrimp for park waters for the period 1983-1987. The important tanner crab fishery occurs in winter and was unobserved in this study. In 1987, 85% of the park tanner crab take was from within Glacier Bay. King crab and shrimp harvest are no longer significant.

The total 1987 commercial harvest within Glacier Bay National Park waters was approximately 2.7 million pounds, valued at $4 million to the fishermen. The processed value was about $8 million. ADF&G uses an economic multiplier of 1.5 to estimate the value of processed fish sales as the proceeds are cycled within the region. Therefore, the total economic value of the harvest from Glacier Bay National Park was approximately $12 million in 1987.

Discussion

The total estimated catch sold by fishermen in 1987 was 2.7 million pounds (1.2 million kg). The actual biomass removed was much higher as most of the fish are sold cleaned. Halibut are sold with their heads off. The halibut "round weight" is about 1.33 times the cleaned weight, according to the IPHC. The 784,000 pounds of halibut sold, therefore, had an original biomass of about 1.04 million pounds (472,000 kg). Crabs are mostly sold whole, so the biomass removed is equal to the sales weight. We estimate that 2.03 million pounds (921,000 kg) of bottom-dwelling

Table 2. Purse seine salmon harvest for GBNP waters. Catches in thousands of pounds of fish.

Fishery	1983	1984	1985	1986	1987
Purse seine:					
Chum	55	473	135	257	457
Pink	1	52	17	3	9
Coho	4	16	5	2	4
Sockeye	0	7	3	1	1
Chinook	0	0	0	0	0
Totals	60	548	160	263	471

Table 3. Halibut harvest for GBNP waters. Catches in thousands of pounds of fish.

Area	1983	1984	1985	1986	1987
Glacier Bay	360	295	413	310	493
Icy Strait	144	118	165	124	197
Outer Coast	38	73	57	88	94
Totals	542	486	635	522	784

Table 4. Dungeness crab harvest for GBNP waters. Catches in thousands of pounds of crab.

Area	1983	1984	1985	1986	1987
Glacier Bay	82	91	119	182	365
Icy Strait	60	9	59	125	74
Dundas Bay	3	0	4	7	17
Outer Coast	444	88	122	93	395
Totals	589	188	304	407	851

Table 5. Tanner crab, king crab and shrimp harvest for GBNP waters. Catches in thousands of pounds of shellfish.

Species	1983*	1984	1985	1986	1987
Tanner crab	478	322	100	200	140
King crab:					
Golden	21	14	1	0	0
Blue	16	10	0	0	0
Red	8	4	0	0	0
Total King crab	45	24	1	0	0
Shrimp	0	0	0	3	1

* 1982 for tanner crab. There was no calendar 1983 opening.

halibut and crab were removed commercially from 973 mi^2 (2520 km^2) of park waters. This is 2,090 lb/mi^2 or 366 kg/km^2. No studies have determined what effect this may have on the marine ecosystem. Commercial crabbers usually fish an area until the catch drops off significantly, then move their pots. The steadily increasing Glacier Bay catch suggests that the populations have not yet been significantly reduced. How long this can continue is debatable. A decade ago, king crab fisheries were booming in Alaskan waters, but today these populations are severely depressed. Overfishing is considered a probable cause.

Commercial fishing activities may impact non-target park populations of cetaceans, pinnipeds and nesting birds. Commercial halibut and crab vessels are operated erratically from set to set, or pot to pot. This kind of vessel operation has been outlawed for visitor vessels to avoid disturbance of whales. Fishermen have been known to shoot sea lions caught raiding commercial salmon gear. Crabbers may soon face an expansion of sea otters into key Dungeness crab waters in the park. Salmon caught in the Excursion Inlet fishery are not available to park bears and eagles along the Excursion River, but no study has determined whether this limits these populations.

Aesthetic and user group conflicts should also be considered. Many visitors consider commercial fishing an inappropriate use of national park resources, although some are interested in the fishing activities and express no objection. Motorized commercial fishing activities conflict with the expectation of solitude and quiet in wilderness waters. In the case of the Beardslee Islands wilderness waters, commercial fishing is a driving political force for deletion of the island waterways from park wilderness. Absent of statutory authorization, should commercial fishing have standing in the setting of national park wilderness or wilderness management policy?

There are issues of fairness also. Should commercial fishing vessels be allowed unlimited entry without need for permits when visitor vessels are being turned away?

Despite the conflicts, the value of the commercial fisheries should not be ignored. The commercial fisheries, particularly those within the inside waters, are important to the local economies of Icy Strait. The people involved are mostly small businessmen, independently sustaining their families and communities by harvesting a renewable, non-oil resource. They export high-quality products to the lower 48 states and to Pacific Rim nations. This is the kind of enterprise that will be needed to sustain the Alaskan economy after the oil is gone. With seafood prices and demand trending upward in recent years, the outlook for commercial fishing is excellent. That outlook, however, can only intensify the conflicts and pressures on park resources. The National Park Service must grapple with these implications, and soon.

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Moose Colonization of Post-glacial Sites in Southeastern Alaska

by

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Abstract

Inhabitants of subclimax habitats, moose *(Alces alces)* were first documented in southeast Alaska in the late 1800s and early 1900s. Many of these sightings were in some of the larger mainland river valleys of the region. Other typical sites include locations recently exposed due to retreat of glaciers. Locations from the Chickamin/Unuk Rivers in the south to Icy Bay/Malaspina Forelands in the north are discussed.

KEY WORDS: Moose, habitats, southeast Alaska.

The moose, *Alces alces,* is the largest cervid in the world, and the Alaska race, *A. a. gigas,* is the largest of all moose. Moose from Alaska, the Yukon Territory, and the Northwest Territories are generally considered to be members of this race. *Alces a. americana* and *A. a. andersoni* include all other Canadian moose and those from Minnesota and Maine, while *A. a. shirasi* includes moose from Utah, Montana, Wyoming, and Washington.

Moose typically inhabit subclimax, fire-maintained habitats, or other locations characterized by disturbed soil and plants often considered pioneer or colonizing species. Riparian, subalpine, and post-glacial areas often provide excellent moose habitat as well. Although interior habitats of Alaska and Canada are often subject to wildfire that returns plant communities to younger stages of development, fires occur relatively rarely in the rain forest of southeastern Alaska. Major moose populations in this part of their range are found along major river valleys, such as the Stikine and Chilkat (Fig. 1), and in areas of recent glacial retreat. Wildfire and river meanderings are fairly frequent phenomena elsewhere which tend to maintain subclimax conditions, often dominated by browse species such as willow *(Salix* spp.) and cottonwood *(Populus* spp.). Because of the time between glacial surges and retreats, however, plant succession often marches on to climax conditions and effectively eliminates moose from areas that may have been good habitat at one time.

Most moose make seasonal movements between calving, rutting, and wintering grounds. Some seasonal movements may be 60 miles or more. Other moose movements appear more tied to emigrations to habitats with browse species at younger stages of development. These younger stages produce more nutritious leaves and stem tips than older plants which put most of their annual growth into wood fiber production. Movements of adult bull moose approaching 200 miles have been documented.

Moose have a high reproductive potential. Cows generally breed at 28 months old, and sometimes at 16 months. Twinning occurs in 15-60% of moose pregnancies; triplets are seen in 1 of 1,000 births. Cows can breed until 16 years of age but probably become less productive after about 12 years of life.

Methods

A review of the literature (Klein 1965; Swarth 1922), anecdotal comments of trappers and hunters, and field notes from past survey efforts of the Alaska Dept. of Fish and Game (1986) provided the information for this paper.

Results and Discussion

The natural establishment of several moose populations in southeast Alaska has occurred in recent years. For both the Yakutat Forelands and the Chilkat Valley, moose were first documented in the late 1920s or early 1930s. Available information for herds on the Unuk, Stikine, and Taku Rivers suggests a similar pattern. Moose in Thomas Bay were undoubtedly migrants from the Stikine herd to the south. Herds in Berner's Bay and the Chickamin River were intro-

Fig. 1. Major river valleys occupied by moose in southeastern Alaska.

duced, although the Chickamin herd never became established. Some sightings of moose exist from the region prior to the 20th century. One report, for example, refers to moose being seen on the Taku River in the 1880s (T. Paul, pers. comm.). If this was a valid sighting, it seems possible that it was the result of the perambulations of an isolated individual and not early population establishment.

Moose in southeast Alaska found their way down major river valleys from interior British Columbia and Yukon Territory. Moving onto range often unexploited by other ungulates, moose thrived and their populations expanded rapidly. The Thomas Bay, Chilkat Peninsula, and Malaspina Forelands populations resulted from expansions of nearby established herds. Moose in Glacier Bay probably came from the Chilkat Peninsula via the Endicott River as well as migrations around the southern end of the peninsula at Point Couverden.

Moose continue to expand into small, isolated patches of habitat which can best be described as extralimital or marginal. Such areas include many of the small islands of central southeastern Alaska (Mitkof, Kupreanof, Kuiu, Wrangell, Etolin, Zarembo, and Woronkofski, for example) and relatively isolated reports from locations such as northern Admiralty and Chichagof Islands. It is doubtful that moose in such locations will ever establish viable herds.

Yakutat and Malaspina Forelands

Moose moved down the Tatshenshini/Alsek corridor and were first seen on the lower Alsek near Dry Bay around the late 1920s. The population expanded to the west, and to a lesser degree to the east (movement being blocked by glaciers and coastal mountains), and by the late 1960s, 2,000-2,500 moose were estimated to be present from the East River to Yakutat Bay. Bull:cow ratios were as high as 50:100, and calf:cow ratios approached 40:100. Due to extremely severe winters, overutilization of browse, predation, and hunting, moose numbers declined to as low as an estimated 300 by 1976.

Moose probably reached Nunatak Bench in upper Russell/Hubbard Fiord in the late 1940s to 1950s and peaked about the same time as the Yakutat Forelands herd.

Moose from the Yakutat Forelands probably reached the Malaspina Forelands on the west side of Yakutat Bay by the late 1950s. The population peak and decline followed a similar time frame as animals on the east side of Yakutat Bay.

While some have speculated that moose here may have come from the Bering River area, Icy Bay is considered by many to be a mostly impassable barrier to moose movement. Furthermore, moose here seem to possess antler and body characteristics more similar to Yakutat Forelands moose rather than those from further west.

Chilkat Valley, Chilkat Peninsula, and Glacier Bay

Moose migrated into the Chilkat River Valley about 1930 and were well established by 1950. The pattern described above for the Yakutat populations was followed here, with peak populations recorded in 1968. Deteriorating habitat, overbrowsing, severe winters, and hunting contributed to population declines in the early 1970s. Since the late 1970s, moose numbers have stabilized, with depressed bull:cow and calf:cow ratios.

Moose were first reported at Glacier Point south of Haines in 1960. In 1963, the same Haines resident making the above observation reported seeing moose at the mouth of the Sullivan River. In 1962, moose tracks were reported from the Bartlett River. In 1965, the first evidence of moose (tracks and one cow) was observed on the Endicott River and St. James Bay. Moose were first seen in Gustavus in 1968. While no moose were seen during ADF&G surveys of Adams Inlet in 1968, a National Park Service report confirmed the first sighting of moose in Sandy Cove in 1967. Regular sightings of moose throughout the Chilkat Range have been made since 1971 with the expansion of moose over Endicott Gap and up the Excursion River.

Summary

Moose moved into southeast Alaska via large river systems bisecting coastal mountain ranges in the early 1930s. Most herds were established on available habitat by the late 1960s. A combination of severe winters, decadent browse, overpopulation, and hunting reduced moose numbers by the early 1970s. By the late 1970s, most herds showed signs of rebuilding. Most recent movement into previously unoccupied range has been in the central southeast Alaska islands, northern Chichagof Island, and Glacier Bay. Essentially all available moose habitat in southeast Alaska is currently occupied.

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Ecology of Brown Bears on Admiralty Island, Alaska: An Overview of Ongoing Research

by

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Abstract

Today, the largest number of brown/grizzly bears in North America occurs in Alaska. In southeastern Alaska, resource development and outdoor recreation are increasing. This paper summarizes an ongoing ecological study, begun in 1981, of brown bears on Admiralty Island. Since that time, 70 bears have been radio-collared and relocated approximately 3,000 times. A major objective of this study was to monitor the effects on brown bears of developing the Greens Creek Mine. The density of brown bears in the study area before mine development was estimated to be 1 bear/2.6 km². Home range characteristics, habitat use, and reproductive data are presented and discussed relative to mine development.

KEY WORDS: Brown/grizzly bears, home range, habitat use, reproduction, mining development, southeastern Alaska.

Once widely distributed across western North America, brown/grizzly bears (*Ursus arctos*) currently range over a significantly reduced portion of the continent and were declared threatened in the United States south of Canada in 1975 (LeFranc et al. 1987). Today, the largest population of brown bears occurs in Alaska (Peek et al. 1987). In southeastern Alaska, logging, mining, and outdoor recreational activities are continually expanding throughout the range of the brown bear. This paper briefly summarizes an ongoing study, begun in 1981, to provide baseline ecological data on brown bears in southeastern Alaska including their seasonal distribution and habitat preference, home range characteristics, reproductive rates and intervals, and den site selection. Additionally, this project was designed to monitor brown bear habitat use before and after mine development near Greens Creek on Admiralty Island.

Study Area and Methodology

Study sites were selected on Admiralty (4,426 km²) and Chichagof (5,341 km²) Islands located within the Tongass National Forest in the northern portion of southeastern Alaska's Alexander Archipelago. Our intensive study site (344 km²) was located on the northern portion of Admiralty Island surrounding Hawk Inlet and included the Greens Creek Mine. This research began in 1981 during the early phase of mine exploration. Major mine development activities began in fall 1985.

Admiralty Island, long considered unique because of its high-density brown bear population, was classified in 1986 by the United Nations' Educational, Scientific and Cultural Organization (UNESCO) as part of the Glacier Bay-Admiralty Island Biosphere Reserve. The lowlands of Admiralty Island are dominated by a dense old-growth rain forest of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*). Broken rock, alpine tundra, and subalpine forests occur above 600 m. Interspersed throughout the forest are poorly-drained muskeg bogs, avalanche slopes vegetated by deciduous shrubs, and numerous rivers and streams which, bordered by riparian spruce communities, provide spawning habitat for several species of anadromous salmon. Extensive wetlands dominated by *Carex* sedge communities occur at the mouths of many streams.

As a consequence of the infrequent opportunities for observing bears inhabiting a dense rain forest, radiotelemetry was chosen as the primary technique for monitoring individual bears. Bears were captured in the alpine zone by darting

with immobilizing drugs fired from a helicopter or were captured in leg-hold snares along fish streams and then immobilized (Schoen 1982). Radio-collared bears were monitored by radio tracking from a fixed-wing aircraft, their locations were plotted on topographic maps, and the habitat attributes (e.g., elevation, slope, aspect, habitat type, distance to fish streams, cover, and human activities) were recorded (Schoen 1982).

Home ranges were determined by connecting the extreme points of the set of relocations to form convex polygons (Mohr 1947). Areas of home ranges were calculated using a polar planimeter. Mark/recapture surveys (using radiocollars as marks) were conducted in alpine habitat during early summer to estimate bear densities in our study area (Schoen and Beier 1988).

Results and Discussion

From 1981 through 1987, 70 brown bears have been radio-collared on Admiralty Island and approximately 3,000 relocations collected. Currently, we are monitoring over 15 bears in the vicinity of the Greens Creek Mine on northern Admiralty Island. Using a mark/recapture survey of radio-collared bears conducted during 1986 and 1987, the density within the northern Admiralty study area was estimated to be approximately 1 bear/2.6 km² (1 mi²). This density is slightly higher than brown bear densities on Kodiak Island (R. Smith, pers. comm.) and considerably higher than densities of brown bears in interior and northern Alaska (Miller et al. 1987, Ballard et al. 1988, Reynolds and Hechtel 1988). This predevelopment density estimate will provide an opportunity to assess long-term effects of the Greens Creek Mine on bear populations.

Significant home range overlap occurred among individual radio-collared bears within the study area. Mean annual home range area for males was 104 km² ($\underline{n}$ = 26, SE = 15.4). Mean annual home range area for females was 33 km² ($\underline{n}$ = 59, SE = 5.5). Individual bears monitored over multiple years displayed strong fidelity to their home ranges. Admiralty Island home ranges were comparable in size with home ranges of brown bears on Kodiak Island (Smith and Van Daele 1984) but much smaller than home ranges of brown bears in northern Alaska (Miller 1984, Reynolds and Hechtel 1986).

Percentage annual use of habitat types by radio-collared bears was as follows: upland and beach fringe old-growth forest (33%), riparian old-growth forest (23%), alpine/subalpine (21%), avalanche slopes (14%), wetlands (5%), and other (4%). Habitat use varied seasonally. During early summer (mid-June through mid-July), most bears moved up to subalpine meadows where they foraged on newly emergent vegetation. From mid-July through early September, most bears moved to low-elevation coastal salmon streams. Riparian habitat, which makes up less than 1% of the study site, received 39% of bear habitat use during this period and is considered critical habitat. By mid-September, many bears began moving toward upper-elevation avalanche slopes and subalpine meadows where they fed extensively on late berry crops.

Although most bears were associated with fish streams during late summer, some bears (primarily females) remained in interior regions of the study area (Schoen et al. 1986). For example, two radio-collared females, monitored for seven years, have never moved to the coast to feed on fish.

Mean dates of den entry and emergence on Admiralty Island were 30 October and 2 May, respectively (Schoen et al. 1987b). Males denned later and emerged earlier than females. Mean elevation and slope of Admiralty Island den sites were 713 m ($\underline{n}$ = 86, SE = 23) and 36 degrees ($\underline{n}$ = 86, SE = 1.2), respectively. Fifty-six percent of Admiralty Island dens occurred in forested habitat. Though cave denning was common on Admiralty, many dens were excavated under large-diameter old-growth trees or into the bases of snags. Further details of brown bear denning ecology are provided in Schoen et al. (1987b).

Data collected from 38 marked females over a 6-year period indicated considerable variability in litter size, age at first reproduction, and breeding interval (Schoen and Beier 1988). Age at first reproduction ranged from 7 to 10 years with a mean of 8 years ($\underline{n}$ = 7, SE = 0.6). Mean litter size for cubs of the year was 1.8 ($\underline{n}$ = 30, SE = 0.1). Cub mortality in the first year of life was 40%. Adult (presumably male) predation on cubs is a probable contributor to high cub mortality.

Major road building activities associated with the Greens Creek Mine began in the lower Greens Creek drainage during late fall 1985 after bears had left fish streams. Road building, including blasting and operation of heavy equipment, continued through 1986 and 1987. During those years, we monitored the movements of up to 12 radio-collared bears along lower Greens Creek from July through mid-September when salmon were spawning. With the exception of two males which increased their use of alternate streams outside the zone of major development, all other bears remained associated with Greens Creek, some within several hundred meters of active development. Intensive telemetry surveys conducted three times per day indicated, however, that bears shifted away from the immediate vicinity of construction activity, then moved closer to the road when activity ceased during late evening. I assume the availability of abundant, high-quality food (e.g., spawning salmon) was a prime factor attracting bears to this area during road building. The dense rain forest apparently provided sufficient cover for most bears to remain in the area during construction activity. However, displacement of bears from Zinc Creek (a small stream

immediately adjacent to the road) did occur. One bear, an adult female displaced from Zinc Creek, moved several hundred meters to Greens Creek where she displaced other (presumably subordinate) bears.

Though 40 to 60 workers were involved in construction of the road, few of these people observed bears in the field (presumably because bears used dense cover to avoid humans), and no bear-human encounters were documented (Schoen and Beier 1988). The lack of bear encounters, and consequently "bear problems," is attributed to several enforced camp policies. Most important was the burning of all garbage several times daily in a fuel-fired incinerator. Additionally, workers were prohibited from: (1) discarding trash or food in the field, (2) recreational hiking, (3) carrying firearms, and (4) hunting or trapping while working on site. Roads at Greens Creek were also closed to public access. Though the final results of this long-term study are still incomplete, these policies, particularly the incineration of garbage and the road closure, significantly reduced the opportunity for bear-human contact and habituation of bears to people.

Use of open-pit garbage dumps by logging camps and small communities, as well as increasing road development, are major concerns of resource managers in southeastern Alaska. For example, because of high bear mortality as a result of increased road access and the inadequate garbage policies of several small communities and logging camps, the brown bear season was closed by emergency order on northeastern Chichagof Island by the Department of Fish and Game in October 1988.

Summary and Conclusions

Admiralty Island, with its diverse and productive habitat base, has one of the highest brown bear densities in the world. Though habitat use by bears varies seasonally, important habitats are riparian old-growth spruce stands associated with anadromous salmon streams, alpine/subalpine meadows, avalanche slopes, and wetland sedge meadows. As a result of abundant and densely packed food resources, home ranges are small with extensive overlap among individuals. Relatively low reproductive rates and high cub mortality occur on Admiralty Island, perhaps as a result of intraspecific interactions, particularly infanticide.

Managing productive brown bear populations in the face of increasing pressures on a finite resource base will not be easy, even in Alaska. As land-use activities intensify throughout the range of brown bears, we must define more clearly the nutritional carrying capacity of bear habitats and understand how zones of human influence affect bear mortality. To maximize the limited resources of bear researchers and managers, better interagency and interdisciplinary cooperation will be necessary. Long-term studies of unexploited populations in undeveloped habitat would provide valuable "benchmark data" for comparative analysis. In southeastern Alaska, the Glacier Bay-Admiralty Island Biosphere Reserve offers an excellent opportunity for collecting long-term benchmark data from two contrasting ecosystems in close geographic proximity. In the final analysis, the long-term future of the brown/grizzly bear will likely depend more on creative people management than on wildlife management per se (Schoen et al. 1987a).

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Relationship Between Prey Abundance and Usage of Glacier Bay by Humpback Whales

by

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Abstract

The distributional relationship between humpback whales *(Megaptera novaeangliae)* and their prey was studied in Glacier Bay and other regions of southeastern Alaska from 1982 to 1985. This study was initiated following a change in whale usage of Glacier Bay. In the 1970s, whales frequently fed in large groups on surface-swarming euphausiids; however, during our 1980s study, whales usually fed alone or in small groups on subsurface fish schools. Surface-swarming euphausiids were not observed in Glacier Bay during the 1982-1985 study; whale feeding patterns depended mainly on the distribution and abundance of fish, including capelin *(Mallotus villosus)*, Pacific herring *(Clupea harengus pallasi)*, and walleye pollock *(Theragra chalcogramma)*. Outside Glacier Bay, humpback whales fed mainly on euphausiids; >80% of the 200+ whales monitored in southeastern Alaska in 1984 fed on euphausiids layered at 60-150 m. Whales returned to some feeding sites, but the location of most feeding whales in southeastern Alaska changed annually.

KEY WORDS: Humpback whales, whale prey, whale feeding, euphausiids, southeastern Alaska, Glacier Bay.

Whaling during the 1900s severely reduced populations of humpback whales *(Megaptera novaeangliae)*. In the North Pacific Ocean, about 1,200 humpback whales remain from a population that was estimated at 15,000 in 1905 (Johnson and Wolman 1984). Currently >300 of the North Pacific whales feed in the inland waters of southeastern Alaska during summer and fall (Baker et al. 1985). An abrupt departure of humpback whales from Glacier Bay (a main whale feeding area in southeastern Alaska) occurred in the late 1970s and was thought to have been caused either by increasing vessel traffic in Glacier Bay or by changes in prey. Beginning in 1982, the National Marine Fisheries Service conducted studies to determine the relationship between distributions of humpback whales and prey in Glacier Bay and other regions of southeastern Alaska (Krieger and Wing 1986). This paper provides an overview of the types, densities, and distribution of whale prey in southeastern Alaska and the importance of prey in determining humpback whale distributions.

Humpback whales enter the inland waters of southeastern Alaska to feed during late spring and reach peak numbers in late summer (Baker 1985). The whales feed both at and below the surface by filtering food between fringed baleen plates arranged in a row along each side of the palate. Humpback whales consume large amounts of prey during their feeding season, with an estimated daily consumption of 1-2 t (Matthews 1978). After summer feeding, most humpback whales migrate to tropical waters and rely on lipids stored in blubber to meet energy demands for breeding and calving (Matthews 1978).

Humpback whales in the North Pacific Ocean feed mainly on fish and euphausiids (Nemoto 1970). In southeastern Alaska, stomachs of humpback whales examined by Andrews (1909) contained only euphausiids. More recent whale prey information for southeastern Alaska has been limited to surface feeding observations; for example, Jurasz and Jurasz (1979) reported humpback whales surface feeding on euphausiids and fish in southeastern Alaska during the 1970s, and Jurasz and Palmer (1981) reported that there were at least 10 whales frequently seen surface feeding on euphausiids in Glacier Bay.

Methods

Whale prey research was conducted from 1982 to 1985 in five regions of southeastern Alaska where humpback whales were known to congregate for feeding: Glacier Bay, northern Chatham Strait, southern Chatham Strait, Frederick Sound, and Stephens Passage (Fig. 1). This paper emphasizes 1984 research; 1984 was the only year in which whales were censused and movements were monitored in all five regions (southern Chatham Strait was monitored once and the remaining regions four times). For simplicity of presenting whale movements, areas adjacent to Glacier Bay in Icy Strait are considered part of the Glacier Bay region, and the southern part of Stephens Passage is included in the Frederick Sound region. Monitoring included sonar assessment and sampling of prey at whale feeding sites, standardized sonar surveys of Glacier Bay and Frederick Sound, and identification of individual whales.

Sonar echosounding and midwater trawling were used to locate and identify types, densities, and distribution of subsurface prey. Sonar surveys, which were repeated at least three times annually, covered a distance of 65 km in Glacier Bay and 73 km in Frederick Sound. Main components of the sonar system were a Biosonics[1] echosounder and integrator and a 104-kHz 7.5° beam-angle Ross transducer. The integrator converts volume scattering data to relative density estimates; echo integration is based on the theory that the average integrated acoustic intensity scattered from targets is proportional to the average density of the targets. Relative densities were converted to absolute densities by applying target strength values for specific species and sizes of whale prey. The distribution of specific whale prey was determined from sonar chart recordings, and the species and size of prey were identified from samples obtained with a 6.0 m^2 opening Marinovich pelagic fish trawl or 1.0 m^2 opening zooplankton Tucker trawl.

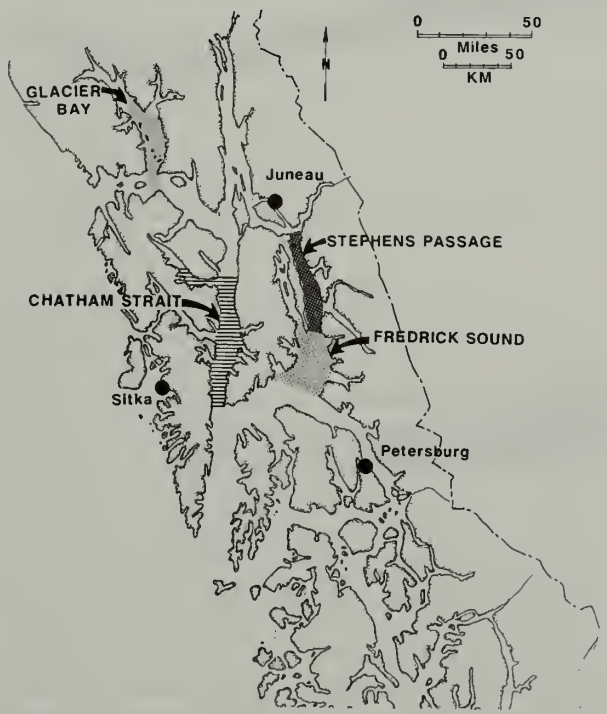

Fig. 1. Southeastern Alaska regions monitored for humpback whales in 1984.

The distribution and abundance of whales was determined by shipboard sightings and photographic identifications. About 20 whales were monitored each year in the Glacier Bay region, and their prey was identified on 200+ occasions from 1982 to 1985. During 1984, about 200 whales were monitored throughout southeastern Alaska and their prey was identified on 300-400 occasions.

Results

Most of the whales observed in the Glacier Bay region from 1982 to 1985 were feeding on subsurface schools of fish, primarily capelin *(Mallotus villosus),* walleye pollock *(Theragra chalcogramma),* and Pacific herring *(Clupea harengus pallasi).* Inside the Bay, capelin was the most common prey. Feeding locations changed frequently inside Glacier Bay, probably because of changes in the distribution of fish schools. For example, in 1982, capelin were abundant in Bartlett Cove (at the entrance to Glacier Bay), and most whale feeding took place there. In 1983 and 1984, however, capelin were not found in Bartlett Cove, and no whales were observed feeding there. Surface-swarming euphausiids were not observed in Glacier Bay during the 1980s, and whales usually fed alone or in small groups on subsurface fish schools that were near the shore in the lower part of the Bay. This feeding differed from observations in the 1970s when Glacier Bay whales frequently fed in large groups on surface-swarming euphausiids, mainly offshore in the middle and upper parts of the Bay. In the Glacier Bay region outside of the Bay boundaries, Pacific herring was the most common prey; most feeding on herring occurred at Point Adolphus, adjacent to Glacier Bay in Icy Strait. Point Adolphus was monitored 45 times (1982-1985) and on each occasion, 2-11 whales were feeding on herring.

Differences were observed in the distribution and density of the three fish species; capelin and Pacific herring were concentrated at 20-50 m depth and walleye pollock were concentrated at < 20 m depth (Fig. 2). Density estimates of whale prey ranged from 100 to 400 g/m^3 for herring and from 4 to 35 g/m^3 for both capelin and pollock; estimates were

[1]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

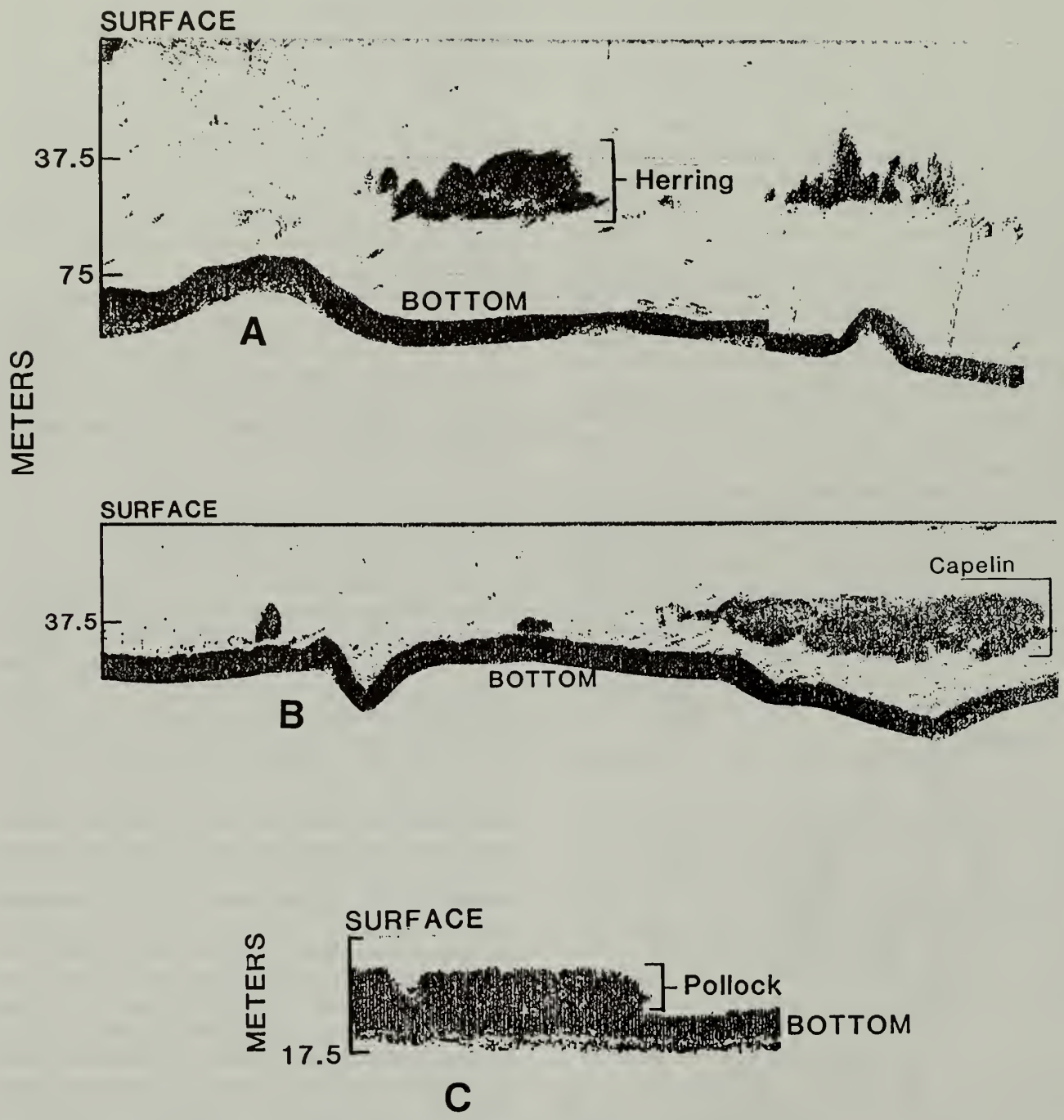

Fig. 2. Echosoundings of humpback whale prey in the Glacier Bay region, southeastern Alaska: (A) herring, (B) capelin, and (C) pollock.

based on target strengths of -66 db/g for 205-mm herring, -66 db/g for 100-mm capelin, and -60 db/g for 74-mm pollock.

Although fish were the main prey of whales in Glacier Bay and in northern Chatham Strait, most whales in southeastern Alaska fed on euphausiids (mainly *Thysanoessa raschi).* In 1984, > 80% of the 200 whales monitored were feeding on dense concentrations of subsurface euphausiids, mainly in the regions of Stephens Passage, Frederick Sound, and southern Chatham Strait (Table 1). Euphausiid layers at whale feeding sites ranged from 20 to 65 m thick between depths of 60 and 150 m. Euphausiids were more abundant at whale feeding sites than in surrounding areas; densities ranged from 1.9 to 30.0 g/m^3 at whale feeding sites but were 2.0 g/m^3 in

Table 1. Prey of humpback whales in southeastern Alaska during 1984. n = number of whales, F = fish, and E = euphausiids.

Region	24-30 Jul		14-22 Aug		30 Aug-7 Sep		11-15 Sep	
	n	Prey	n	Prey	n	Prey	n	Prey
Glacier Bay	14	F	17	F	7	F	5	F
Northern Chatham Strait	11	F	8	F	--	--	8	F
Frederick Sound	35-45	E	40-60	E	8	E	4	F&E
Stephens Passage	2	E	12	E	60-80	E	40-50	E
Southern Chatham Strait	--	--	30-40	E	--	--	--	--

Table 2. Number of humpback whales (in parentheses) and euphausiid densities (g/m^3) in Doty Cove, southeastern Alaska, 1983-1985.

Year	15-31 Jul	1-15 Aug	1-5 Sep	6-10 Sep	11-15 Sep	16-20 Sep
1983	--	--	--	6.0+ (20)	--	1.9 (8)
1984	0.9 (0)	1.8 (0)	6.2 (25)	--	--	1.9 (9)
1985	1.7 (0)	5.9 (0)	6.8 (0)	10.0 (2)	8.9 (2)	5.7 (4)

areas without feeding whales (Fig. 3). Densities were based on a -68 db/g target strength for euphausiids that ranged in size from 12 to 15 mm.

Whales returned each year to a few feeding sites in Stephens Passage where dense euphausiid layers formed in late summer. Prey densities and whale numbers were monitored at one of these sites (Doty Cove) from 1983 to 1985; the declining euphausiid densities appeared directly related to the number of feeding whales (Table 2). In 1983 at Doty Cove, there were 20 whales feeding on euphausiids in early September, but by mid-September, euphausiid densities had decreased substantially, and the number of whales had decreased to eight. In 1984, whale numbers increased from 0 in July to 25 in early September and then decreased to 9 by mid-September, coincident with euphausiid densities that increased sevenfold from late July to early September and then decreased by a factor of 3 by mid-September. In 1985, euphausiids again increased to high densities by early September, but did not decline sharply as in the previous two years, probably because only a few whales fed in Doty Cove during September 1985.

The distribution of most whales in southeastern Alaska was related to the distribution of dense euphausiid layers. During early summer 1984, most of the whales were feeding in Frederick Sound or southern Chatham Strait, the only two regions where abundant euphausiids were found. By late summer, euphausiid densities increased in Stephens Passage, and most whales were feeding in this region. Whales traveled to euphausiid-rich sites in Stephens Passage from all other regions monitored in 1984, but no travel was observed from euphausiid-rich regions to fish abundant regions. Travel to Stephens Passage included 4 of the 24 whales identified in the Glacier Bay region, 2 of the 16 whales identified in northern Chatham Strait, and 12 of the 58 whales identified in Frederick Sound.

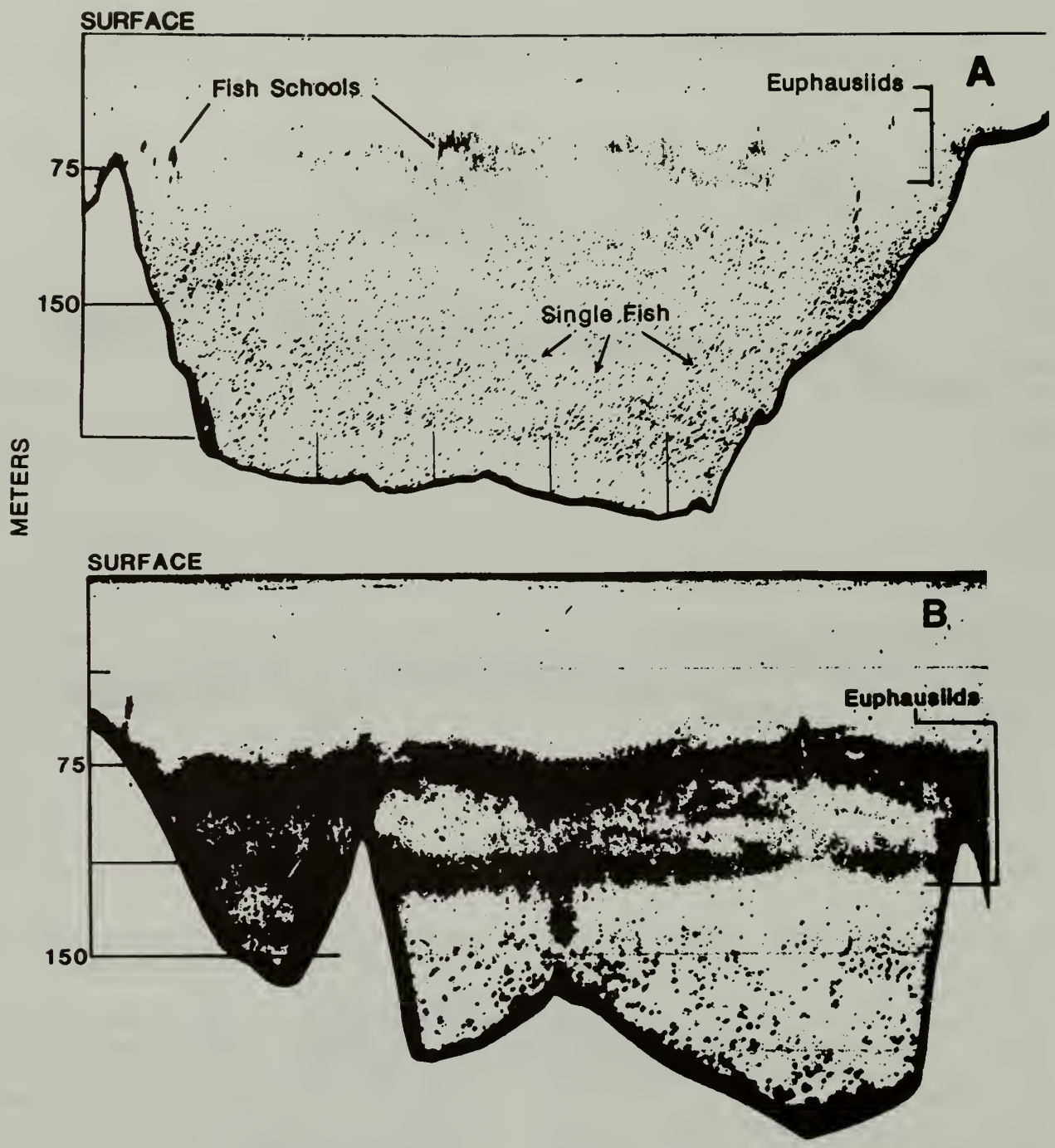

Fig. 3. Echosounding of (A) the general distribution of fish and euphausiids in southeastern Alaska and (B) a euphausiid layer at a humpback whale feeding site.

Summary

A decrease in surface-swarming euphausiids appears to be the main reason for the change in the use of Glacier Bay by humpback whales. In the 1970s, large groups of whales congregated offshore to feed on surface-swarming euphausiids. During our whale prey study in the 1980s, surface-swarming euphausiids were not observed in Glacier Bay, and whales fed almost exclusively on fish schools. Feeding consisted mainly of one or two whales foraging close

to shore. Whale feeding locations changed frequently in Glacier Bay, probably in response to changes in the location of fish schools.

Sonar monitoring of subsurface whale prey provided an increased understanding of whale feeding in southeastern Alaska; monitoring of whale feeding sites revealed that most whales fed on euphausiids layered between 60 and 150 m. Spatial monitoring of prey identified the discreteness of high prey concentrations and the ability of whales to locate these patches of prey. Some whales returned to feed at certain sites, but most changed location annually. Although whales in Glacier Bay and northern Chatham Strait fed mainly on fish, the distribution of most whales in southeastern Alaska was directly related to the distribution of euphausiids.

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Killer Whales in Glacier Bay and Icy Strait, Alaska

by

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Abstract

The abundance, distribution, and behavior of killer whales *(Orcinus orca)* in Glacier Bay and adjacent waters of southeastern Alaska were documented from a sighting network of tour vessel operators, National Park Service personnel, local fishermen, and private boaters. Sighting records indicated that killer whales were present in the Glacier Bay area a minimum of 55 of 107 days in the summer season (June 1 through September 15) of 1988. Intervals between these sightings suggested that individual killer whale groups were not present in the area throughout the summer but appeared to frequent the Glacier Bay and Icy Strait region for periods of 1 to 11 days as part of a larger seasonal or migratory range that is, as yet, incompletely described.

Individual killer whales were identified from photographs of natural variation in the shape of their dorsal fins and the distinctive pattern of white pigmentation along their backs and sides. The analysis of photographs collected between 1984 and 1988 indicated that a minimum of 71 individual killer whales, representing 11 different pods, have visited the Glacier Bay area. Comparison of these photographs with a larger catalog of photographs from throughout southeastern Alaska, Prince William Sound and the Vancouver Island—Puget Sound region confirmed the presence of two distinct behavioral and morphological types of killer whales, referred to as "transients" and "residents." Transient-type killer whales, which tend to travel in small groups and are reported to eat other marine mammals as well as fish, were encountered most frequently in the Glacier Bay area. Individuals of this type sighted in Glacier Bay have been shown to range as far away as Vancouver Island, British Columbia, a distance of over 1,200 kilometers. Resident-type killer whales, which form large stable groups and are reported to feed mainly on fish, were encountered less commonly in the Glacier Bay area. However, one large resident-type pod sighted regularly in Prince William Sound, Alaska, was also sighted in the Glacier Bay area, documenting a range of over 900 kilometers.

KEY WORDS: Killer whales, pods, resident-type, transient-type, abundance, range.

Study of the behavior and natural history of free-ranging killer whales *(Orcinus orca)* began in the early 1970s when biologists in British Columbia and Washington state became concerned about the number of killer whales being live-captured for use in aquaria. They discovered that minimum population estimates of killer whales could be made by censusing individuals identified from photographs of natural variation in the shape of the dorsal fin and saddle patch, a white pigmented area at the base of the dorsal fin (Bigg et al. 1976). Adult male and female killer whales are easily distinguished in the wild by dimorphism in their overall size and the height of their dorsal fin. Adult males have a more triangular dorsal fin that may reach six feet in height, while the dorsal fin of females is shorter and often more hooked or falcate. Subadults, however, are not easily distinguished from adults, but if individually identified, can be sexed upon sexual maturity. Thus, photoidentification of individuals has allowed longitudinal studies which are beginning to elucidate the details of the social organization and life history, as well as distribution and abundance, of this intriguing species (Bigg et al. 1987).

Intensive studies of photoidentified killer whales have centered on two regional populations: Prince William Sound, Alaska, and southern British Columbia-Puget Sound. Based on morphological differences, vocal dialects, and the size and feeding habits of the pods, it became apparent that these regions were frequented by two distinct types of killer whale pods: residents and transients (Bigg et al. 1976; Balcomb et al. 1980; Bigg 1982; Ford and Fisher 1982).

Resident pods are larger and socially cohesive, usually containing between five and fifty individuals. Pods appear to form along matrilineages, and females do not leave their natal pod. Resident pods tend to travel in a predictable manner in open water from headland to headland and vocalize frequently, using between five and fifteen communication calls. As their name implies, some resident-type pods establish predictable local home ranges during part of the year. However, resident-type pods have been observed to travel distances of 900 kilometers and may show different ranging patterns in different habitats. Resident-type killer whales are primarily or exclusively fish eaters (Bigg et al. 1987).

Transient pods travel in smaller groups of one to seven individuals, and the social structure of these groups appears to be fluid. The movement of transient pods is much more unpredictable. Entering inner bays and narrow waterways in search of smaller marine mammals, these pods are usually silent and have an overall vocal repertoire of only three to four different communication calls. Transients are reported to range farther than the residents, ranging up to 1,200 kilometers along the Pacific coast from Puget Sound into southeastern Alaska. Resident- and transient-type killer whales are not observed to mix or travel together and are thought to be reproductively isolated from each other (Bigg et al. 1987).

Resident-type killer whale pods appear to be the predominant type in the inshore waters of both British Columbia-Puget Sound and Prince William Sound. Resident-type killer whales occur year round in British Columbia-Puget Sound where they form two communities with exclusive home ranges. Approximately 85% of the 332 individuals photo-identified in this region are resident-types (Bigg et al. 1987). Similarly, Prince William Sound is frequented by ten separate pods representing nearly 200 individuals, of which about 85% are resident-type (Matkin et al. 1987). Unlike British Columbia, however, the resident pods of Prince William Sound all have overlapping ranges, sometimes coming together in concentrations of "super-pods" of 50 to 75 individuals. Although there are seasonal shifts in centers of abundance, the southwestern part of Prince William Sound seems to be a "preferred area" (Matkin and Matkin 1981).

Killer whales in southeastern Alaska have received far less study than those in Prince William Sound or British Columbia-Puget Sound. In 1984, an intensive season of study was conducted by Hubbs-Sea World in hopes of being able to capture some individuals for public display. During this 1984 study, a total of 96 individuals, representing nine pods, were photoidentified. Fifty-six of these individuals, representing five different pods, were sighted in the Glacier Bay-Icy Strait area. Overall, 40% of the animals identified were transient-types (Leatherwood et al. 1984).

A comparison of photographs from all three studied regions demonstrated that the ranges of some pods from both British Columbia and Prince William Sound overlap in southeastern Alaska. However, there was no overlap of pods from Prince William Sound with pods identified in British Columbia (Leatherwood et al. 1984). One resident-type pod (AF) first identified in Prince William Sound was observed several times in the Glacier Bay-Icy Strait area, completing at least one round-trip between the two regions in July 1984. From these sighting records, it appears that a resident-type designation among Alaskan killer whales does not refer as much to a local home-ranging pattern as it does to the whales being a certain type of pod or family group.

Here I present the preliminary results of a study of killer whale habitat use in Glacier Bay and the adjacent waters of Icy Strait. These results confirm and extend those of the previous studies reviewed above and demonstrate that killer whales previously identified in both Prince William Sound and British Columbia-Puget Sound are frequent visitors to the Glacier Bay area.

Methods

The seasonal distribution of killer whales in the Glacier Bay-Icy Strait area was documented by a sighting network of tour vessel captains, National Park Service biologists, rangers, and naturalists as well as local fishermen and private boaters. Although these sightings were collected on an opportunistic basis, they included the reports of captains and naturalists aboard the two regularly scheduled tour boats which operated in Glacier Bay each day. The generally standardized course of travel and continuity of personnel aboard these two vessels provided some degree of consistency and reliability to the sighting network within the bay. Observation platforms in the adjacent waters of Icy Strait were far more sporadic and coverage far more incomplete.

Natural markings of killer whales were photographed with high-speed black and white film using 35-mm, single-lens reflex cameras equipped with motor drives and 200mm, 300mm, or 70-210mm telephoto lenses. Photographs were collected on an opportunistic basis during 1988 by National Park Service biologists Scott Baker and Jan Straley, Nigel Atherton on the cruise ship *Island Princess,* and the author. Photographs of killer whales collected in the Glacier Bay area by Scott Baker during the years 1986 and 1987 were also included in the analysis. These photographs were compared to the existing photoidentification catalog of killer whales from southeastern Alaska, Prince William Sound, and British Columbia-Puget Sound by Graeme Ellis of the Pacific Biological Station (Department of Fisheries and Oceans), British Columbia. Pod identity designations and animal numbers follow those used in previous publications (Leatherwood et al. 1984; Bigg et al. 1987).

Results and Discussion

The sighting network revealed that these animals were frequent visitors to the Glacier Bay area during the summer of 1988. One or more killer whales were reported on 55 of 107 days between 1 June and 15 September and were observed with nearly equal frequency in all summer months, primarily near shorelines on the west side of Glacier Bay. These sighting records, and those reported previously by Leatherwood et al. (1984), suggested that killer whale use of Glacier Bay-Icy Strait is unusually high in comparison to the rest of southeastern Alaska, although lower than in Prince William Sound and British Columbia-Puget Sound.

Seventy-one individual killer whales, representing eleven different pods, have been photoidentified in the Glacier Bay-Icy Strait region since 1984. Small groups of transient-types are most common in this area, although a "super-pod" of 30 to 40 resident-types was observed 18 August 1986 in Icy Strait. The two resident pods (AF and AG) previously documented in this area by the 1984 Sea World group were again photographed here in 1986, as well as one transient individual (T2) not previously documented in this area,

Table 1. Summary of photoidentification records of killer whales in the Glacier Bay-Icy Strait area during 1986 and 1987.

Date	Pod	Individual Identification #	Location	Previous Sightings*
8-15-86	T	2	Glacier Bay	1976 – BC
8-18-86	AG	1, 4, 5, 6, 7, 8, 9, 11	Icy Strait	1983 – GLBA 1984 – IS & GLBA
8-18-86	AF	5, 11, 15, 18, 20, 21	Icy Strait	1983 – PWS 1984 – FS, IS, & PWS
5-29-87	AH	1, 3, 4, 5, 6	Icy Strait	1984 – IS
7-16-87	T	2	Glacier Bay	1976 – BC 1986 – GLBA
7-17-87	AQ	2	Glacier Bay	1984 – SP
7-17-87	Z	1	Glacier Bay	BC
7-28-87	AQ	2	Icy Strait	1984 – SP 1987 – GLBA
7-28-87	Z	1	Icy Strait	BC 1987 – GLBA
7-28-87	P	1	Icy Strait	BC
7-28-87	O	10, 11, 12	Icy Strait	BC
7-28-87	AH	1	Icy Strait	1984 – IS 1987 – IS
7-30-87	AG	2, 3, 4, 5, 6, 7, 8, 9, 11	Glacier Bay	1983 – GLBA 1984 – IS 1986 – IS

* BC = British Columbia; GLBA = Glacier Bay; IS = Icy Strait; PWS = Prince William Sound; FS = Frederick Sound; SP = Stephens Passage; CS = Chatham Strait.

Table 2. Summary of photoidentification records of killer whales in the Glacier Bay-Icy Strait area during 1988.

Date	Pod	Individual Identification #	Location	Previous Sightings *
6-19-88	AL	3, 4, 10, 13, 14, 15	Glacier Bay	1983 – FS 1984 – IS
7-03-88	AO	1, 2, 3, 4	Glacier Bay	1979 & 1983 – FS 1984—IS & FS
7-03-88	AL	3	Glacier Bay	1984 – IS 1988 – GLBA
7-03-88	T	2	Glacier Bay	1976 – BC 1986 – GLBA 1987 – GLBA
7-03-88	M	3	Glacier Bay	BC
8-05-88	AL	4	Glacier Bay	1988 – GLBA
8-05-88	M	1, 2, 4	Glacier Bay	1988 – CS & BC
8-15-88	AF	1, 6, 7, 8, 10, 16, 19, 21, 22	Glacier Bay	1984 – IS & PWS 1986 – IS
10-26-88	AL	5	Icy Strait	1984 – IS

* BC = British Columbia; GLBA = Glacier Bay; IS = Icy Strait; PWS = Prince William Sound; FS = Frederick Sound; SP = Stephens Passage; CS = Chatham Strait.

making a total of 15 individuals identified that year. Four new transient pods (AQ, Z, P, and O), including six individuals, were identified in Glacier Bay and/or Icy Strait in 1987, although seven pods (including AH, T, and AG) or 21 individuals were identified for that year. One male transient (T2), that had not been observed since 1976 in British Columbia waters, was documented in Glacier Bay and/or Icy Strait in 1986, 1987, and 1988.

One new transient pod (M) was added in 1988, while five different pods (including AL, AO, T, and AF), eight new individuals, or 25 total individuals were positively identified to date. One of these new transient individuals (M1) was documented in Chatham Strait, Alaska, in late June of 1988, in Glacier Bay in early August, and 26 days later in Johnstone Strait, British Columbia (Graeme Ellis, pers. comm.).

Although killer whale use of the Glacier Bay area is relatively high compared to other areas of southeastern Alaska, it does not appear to be part of the exclusive home range of any given pod. The distribution of reported sightings suggested that individuals or pods remained in the Glacier Bay area between one and eleven days before departing for other habitats.

Opportunistic photoidentification indicated that a number of different pods may frequent the Glacier Bay area during a given summer (Tables 1 and 2). Some pods were documented to have frequented this area several times during the summer, and some may return to this area across years (Tables 1 and 2). Within-year resightings were documented for members of pods AH, AQ, Z, AL, and M. Sighting intervals ranged from between eleven days and two months. Although the shorter intervals may have indicated continuous occupancy of Glacier Bay, the absence of intervening sightings during the longer intervals suggests that these are the result of return visits. Across-year sightings were documented for members of pods T, AG, AH, and AF.

Photoidentification data confirm previous reports that the Glacier Bay-Icy Strait area, and possibly all of southeastern Alaska, is a zone of overlap between individuals or pods

which range as far south as British Columbia and other pods which range as far north and west as Prince William Sound (Tables 1 and 2) (Leatherwood et al. 1984). For example, pods T,Z,P, and O were sighted in British Columbia and Glacier Bay while pod AF was documented in Prince William Sound and Glacier Bay. No pods have been documented to traverse the entire range from British Columbia to Prince William Sound.

The primary prey species of killer whales in the Glacier Bay area is unknown. Some evidence of predation on salmon was observed inside Glacier Bay and on a Steller sea lion *(Eumetopias jubatus)* in Icy Strait (Jan Straley, pers. comm.). Killer whales in Glacier Bay have been observed moving among ice floes and reefs that were occupied by intensively vocalizing and excited harbor seals *(Phoca vitulina)* (Kris Hartnett and Janet Warburton, pers. comm.). Humpback *(Megaptera novaeangliae)* and killer whales have been observed in close proximity to one another at Point Adolphus in Icy Strait, an area rich in herring, salmon, harbor porpoise *(Phocoena phocoena)*, seals, and sea lions. Individuals of both whale species have appeared to feed in the same tide rip.

Further investigation of prey species is needed, particularly in light of the controversy over newly acquired feeding habits of killer whales in other regions. In Prince William Sound, one resident-type pod responds to the sounds of long-lines full of black cod and halibut being brought to the surface and strips these lines of their fish. The commercial fishermen involved have at times resorted to shooting the whales and have killed as many as ten members of this pod (Matkin et al. 1987). It is conceivable that this could become a management problem in the bottom fisheries of the Glacier Bay-Icy Strait area.

This preliminary project has raised many questions that remain to be answered. Is killer whale use of the Glacier Bay marine habitats increasing? Is there a seasonal variation in killer whale use of this area? What percentage of killer whales that pass through Icy Strait ultimately enter Glacier Bay? Are the feeding patterns and preferences of residents and transients different here than they are in Prince William Sound and British Columbia?

Future goals are to (1) photoidentify all new pods and individuals encountered to enable the classification of these animals into age/sex classes, (2) monitor births and deaths in order to calculate vital statistics, and (3) determine specific areas of abundance and feeding patterns. As information is compiled and shared by researchers in all areas, many of the secrets of these fascinating animals will become new knowledge.

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Consistency and Change in Subsistence Use of Glacier Bay, Alaska

by

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Abstract

Glacier Bay has long been an important area for subsistence hunting and fishing by the Huna Tlingit of northern southeast Alaska. Historically, Glacier Bay and much surrounding area was owned by Tlingit clans who have inhabited and used the bay for at least the past 2,000 years as glacial advances and retreats permitted. Traditional activities included harvest of wild foods such as salmon, halibut, shellfish, goat, seals, birds and bird eggs. The creation of Glacier Bay National Monument in 1925, its expansion in 1939 and its designation as a national park in 1980 have resulted in government policies and regulations that first discouraged and later prohibited most subsistence activities in and around the bay.

The evolving legal framework for subsistence use in Alaska recognizes subsistence rights by rural residents, including residents of the contemporary Tlingit village of Hoonah. This has resulted in renewed interest in traditional uses of the Glacier Bay area. A management program for Glacier Bay National Park is discussed that acknowledges the cultural context for the park and addresses contemporary subsistence issues and concerns.

KEY WORDS: Subsistence, Glacier Bay, Hoonah, Tlingit.

Evidence for early human occupation of the Glacier Bay area is available from a site at Ground Hog Bay near Point Couverdon, indicating aboriginal presence that closely followed the end of the Wisconsin glaciation (Ackerman 1984). A stabilization of sea levels followed the melting of the great Wisconsin glaciers, leading to conditions suitable for the expansion of salmon and shellfish populations along Alaska's southern coasts. These coastal resources are considered to be essential parts of the foundation for the development of Pacific Northwest aboriginal cultures (Ackerman 1968, Langdon 1983). The Tlingit and their predecessors have most probably lived in the Glacier Bay and Icy Strait area for the past 9,000 years. Occupation was probably continuous during the past 2,000 years, with the Tlingit taking periodic advantage of glacial retreats to establish seasonal camps, hunting and fishing sites, villages and clan houses within Glacier Bay. Localized glacial activity, more recent than the Wisconsin glaciation, has obliterated any sign of the prehistoric use of Glacier Bay itself. Tlingit legends, in the form of clan-owned stories that are still told today, provide the accounts of occupation of the bay during the post-Wisconsin (Holocene) prehistory.

The people who made the Icy Strait area their home came to be known as the Huna Tlingit, and for the past few hundred years their activities and territories have been described in the writings of Russian explorers, missionaries, anthropologists and adventurers. Early accounts from the Russian explorer Chirakov, who approached Icy Strait in July of 1741, describe the sighting of Natives, presumably Huna Tlingits, who may thus have been the first Native Americans in northwest North America to have made contact with Europeans (Langdon 1980, Krause 1956).

In the period from contact to about 1880, the Hunas lived in from two to four villages. The principal village was Gaudekan, at the present site of Hoonah, which in the late 1870s was estimated to consist of 13 large houses with about 600-800 people (Krause 1956). Other villages were located at Ashley Entrance near Point Couverdon, Village Point on the mainland adjacent to Porpoise Island and in Excursion inlet at the site of the present cannery. In addition to these sites, other villages and forts are mentioned by Huna sources, at Dundas Bay, at Berg Bay, Bartlett Cove, Drake Island, and Point Carolus in Glacier Bay, Port Frederick and on Inian and Lemesurier islands. Clan houses are reported to have

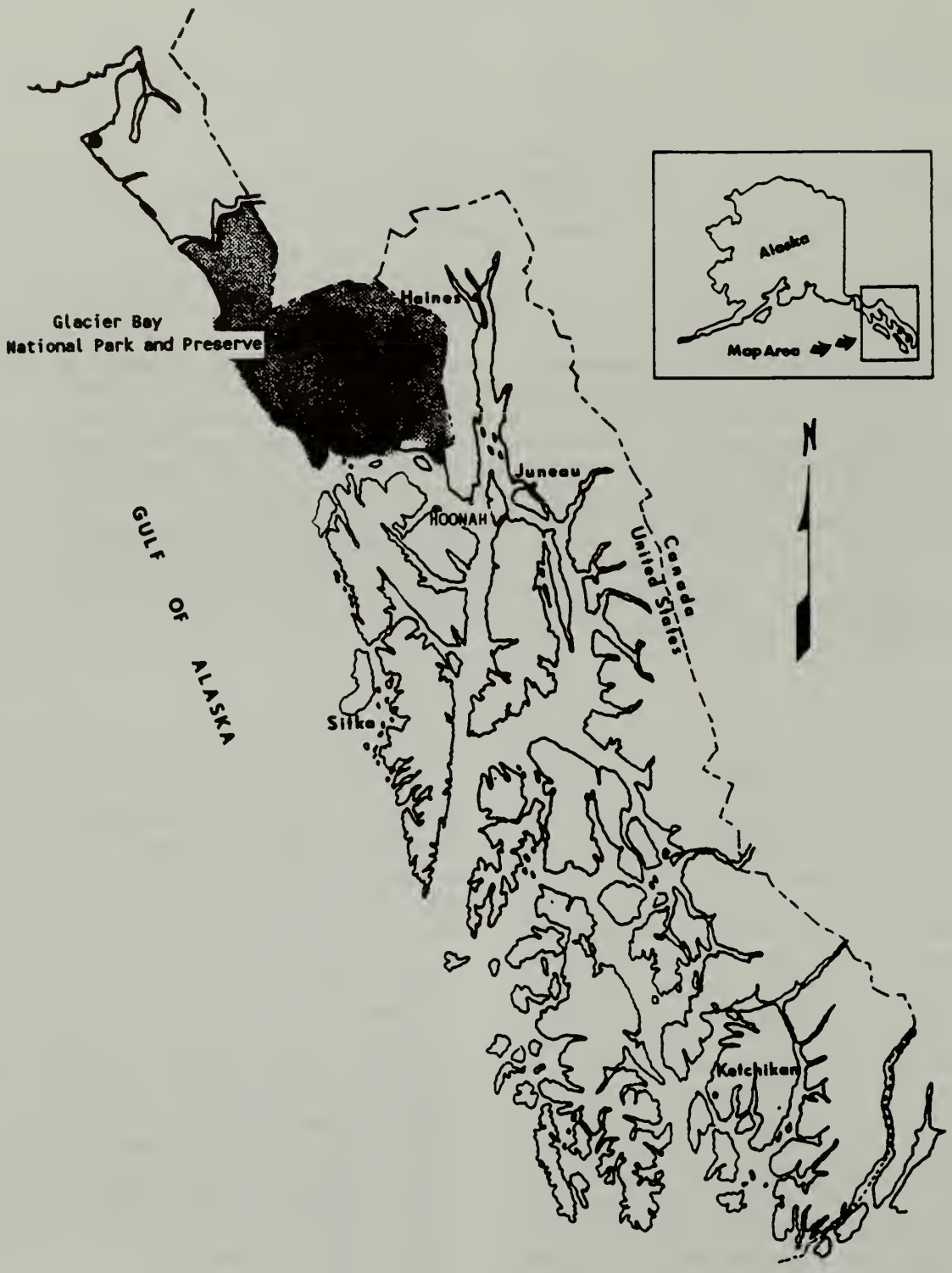

Fig. 1. Location map, Glacier Bay National Park and Preserve.

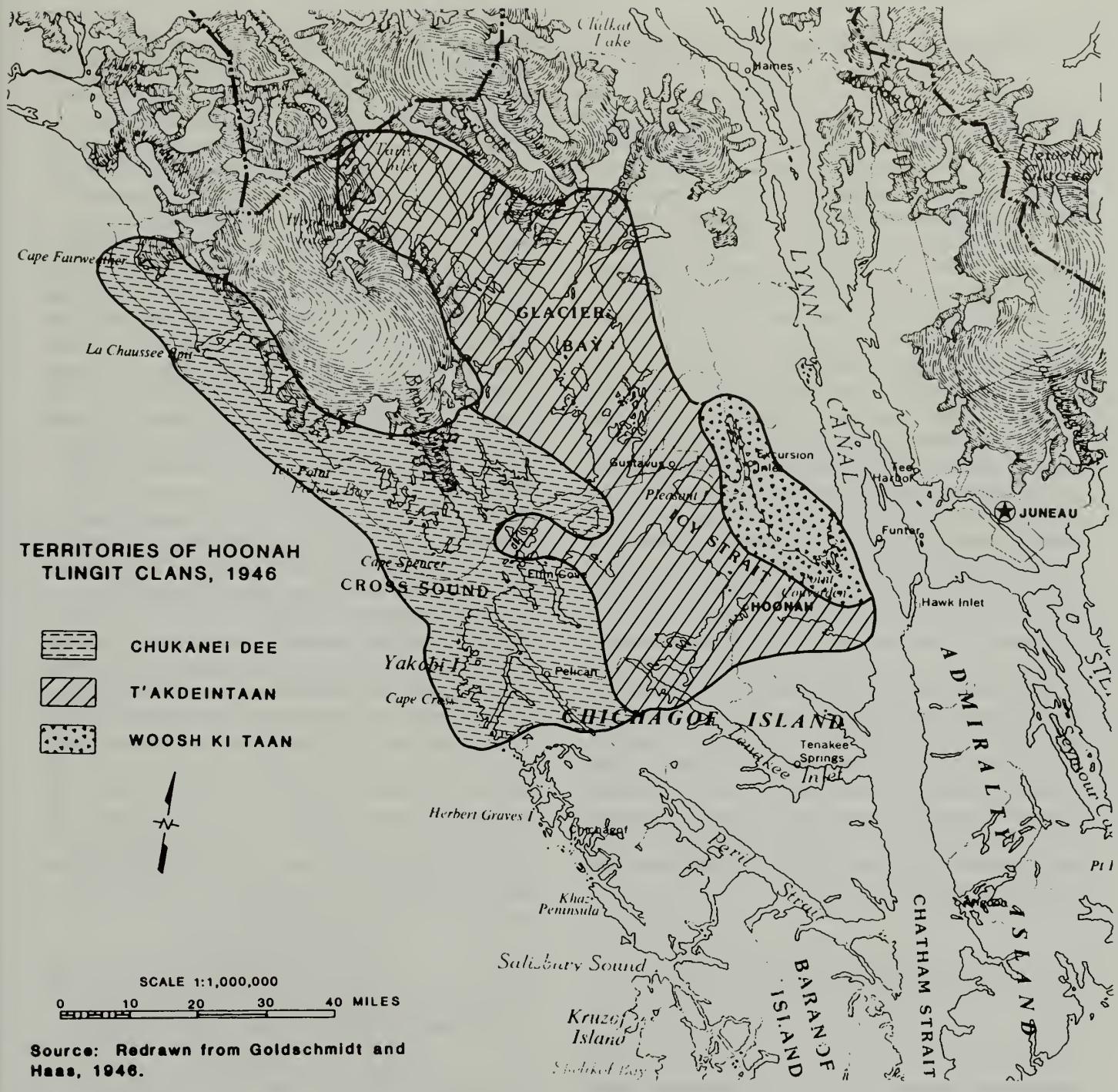

Fig. 2. Clan boundaries of the Huna Tlingit. (Redrawn from Goldschmidt and Haas 1946.)

existed at the entrance to Glacier Bay and along the Bartlett River. Clan houses eventually built at Hoonah were given names ("Upper House," "Middle House," "Iceburg House") that originally belonged to the Bartlett River houses. Smokehouses at Bartlett Cove were still in evidence early in this century (Goldschmidt and Haas 1946; Ackerman 1968).

Centralization of the Huna Tlingit, as with other tribes in the region, took place in the early twentieth century in response to commercialization of the fisheries and the requirements of compulsory schooling. By the mid 1930s, the Huna had consolidated, and most had located permanently at the village of Hoonah (Fig. 1).

Occupancy and Use of Glacier Bay

Icy Strait and Glacier Bay were an integral part of the Huna territory. Within Glacier Bay, areas adjacent to tidewater glaciers were often the site of seal hunting camps, while the lower reaches of the bay provided the greatest overall diversity of wild foods. Of all this area, Bartlett Cove is said to have been the most important location for the procurement and processing of foods. Place names for Glacier Bay, reflecting the significance of this area, have been translated as "the main place for the Huna People," and "the Huna breadbasket." Nearly every item in the domestic economy of these Icy Strait residents could be obtained in Glacier Bay.

At the time of contact, concepts of property and ownership, including ownership of land and of hunting and fishing areas, were well established among the Tlingit. Glacier Bay was owned by the Tckukanedi and Wukitan clans, people who now reside primarily in the village of Hoonah. Outside of the bay, coastal areas were apportioned among several other Huna clans. Sockeye salmon stream systems were especially highly valued food-gathering locations, and sockeye streams in the vicinity of Hoonah were divided among at least three Huna clans: the Tckukanedi, Daqdentan, and Wukitan (Fig. 2). In many cases resource territories were shared among clans, as appears to have been the case at the Inian Islands, which the Tckukanedi clan owned, occupied and used to dry halibut, gather seaweed and hunt seal and deer but which was shared with Daqdentan clan. In addition to salmon streams, resource territories included hunting areas, berry and root gathering areas, hot springs, trade routes and shellfish grounds. Claims to resource areas often were codified in the form of totem poles and potlatches commemorating ownership of important sites and substantiating the claim of an individual clan head to the territory that the clan claimed (Langdon 1983, Goldschmidt and Haas 1946).

Conflicting Concepts of Land and Property Ownership

Exploitation of natural resources in the Pacific Northwest by nineteenth-century explorers and colonizers eventually resulted in conflicts when the newcomers either ignored or disputed the established Tlingit systems of land and resource ownership.

Conflict over property and ownership concepts were first illuminated in 1867 with the United States' purchase of Alaska from Russia. The Tlingit greatly objected to the sale and made it clear that the purchase was impossible, since the Russians did not own the land in the first place. On the contrary, it was clear to them that they had allowed the Russians to occupy the lands in the vicinity of Sitka for their mutual benefit. The Alaska purchase, however, was soon to be characterized by a strong military presence designed primarily to assert ownership rights and to protect American citizens in their efforts to exploit the new Territory's resources.

Commercial exploitation of the salmon resource by the new wave of American entrepreneurs began the next phase of conflict over property and resource ownership in the region. Salteries and canneries began to be established in Southeast Alaska in the period from 1867 to 1878, and initially they depended on maintaining friendly ties with the acknowledged Tlingit owners of productive salmon streams. One report indicates that the head of the Daqdentan clan in Hoonah, trustee of sockeye systems on the north shore of Icy Strait, west of Glacier Bay, had accepted a fee for the land and fish that would be needed by a cannery in Dundas Bay. The fee was to be paid annually, and members of the Daqdentan clan fished in the streams and sold fish to the cannery (Langdon 1983).

This period of minimal conflict and relatively modest resource exploitation was short lived. The bombardments of both Kake in 1869 and Angoon in 1882 by U.S. Naval vessels were calculated efforts to assert military authority in the region; these events additionally asserted the rights of American citizens to exploit salmon as a seemingly inexhaustible common property resource. By the mid-1890s, recognition by canneries of clan ownership and property concepts began to deteriorate, and the advent of U.S. Government "gunship policies" effectively inhibited Tlingit efforts to protect their resource and property rights. The commercial salmon fishing and the Pacific canned salmon industries expanded rapidly in this political climate. The mining industry also gained momentum in these years; the first gold mining camp in Alaska was established at Windham Bay in 1878, and by the end of the century, large gold deposits had been discovered at Juneau.

Federal Land Policy and the Creation of Glacier Bay National Monument

Federal land policies in southeast Alaska evolved in the early 1900s with the growing recognition of the natural resource wealth of the new Alaska Territory. This was reflected in the designation of the Tongass National Forest in 1907, which took place during a time when the American public strongly supported retention of federal lands as parks or forest reserves. Management of the Tongass was intended from its beginning, however, to focus on the purely utilitarian goals of harvesting the region's vast timber resource and building a regional economic base.

Public interest and debate on Alaskan issues soon turned to the scenic, recreational and wildlife values of the new Tongass National Forest and the little-known Glacier Bay area. Scientific interest in Alaska began in these years as well, leading, in Glacier Bay, to the first systematic studies of glaciology and plant succession.

This growing recognition of the scenic and scientific virtues of Glacier Bay prompted the Ecological Society of America, in 1923, to propose that Glacier Bay and its environs be established as a national monument, managed by the National Park Service (NPS). The Ecological Society proclaimed Glacier Bay to be "totally uninhabited and underdeveloped," a consideration that they believed argued favorably for prompt action on the monument proposal (Cooper 1956). In 1925 Glacier Bay National Monument was created by executive order of President Calvin Coolidge; in 1939 President Roosevelt enlarged the monument considerably by adding much of the lower bay, the outer coast and surrounding uplands (Fig. 3).

The proclamations that ultimately established Glacier Bay National Monument and then enlarged it are mute on the subject of the use of Glacier Bay by the Huna Tlingit or any aboriginal rights to the bay, noting (in the 1925 proclamation) that the bay's historical significance dates to the 1794 voyage of Vancouver. But there is no evidence of any real conflict over the use of the bay until the 1940s, and it may be assumed that the limited visitation, scientific study or government regulation that did occur in the early years of the monument had little effect on food gathering or other activities of the Tlingit.

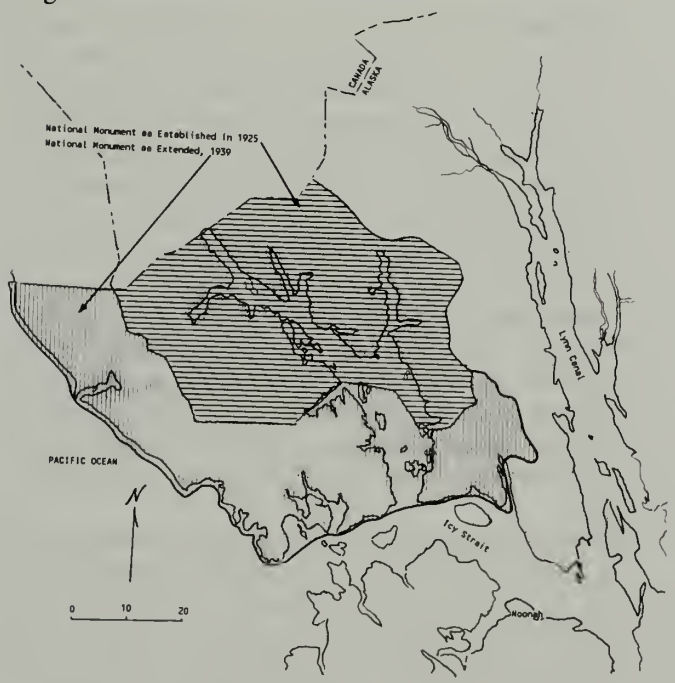

Fig. 3. Glacier Bay Monument boundaries, 1925, 1939.

Changing Regulations and Changing Use of Glacier Bay

Prior to 1939, monument boundaries had not extended into important fishing, hunting and egging areas, but when boundaries were enlarged, egging and most hunting at these traditional sites was no longer allowed. Shortly thereafter, for conservation reasons, fishing areas in Dundas Bay, which had been greatly depleted by the use of fish traps by the canned salmon industry, were also closed by the U.S. Fish and Wildlife Service (Black 1957).

In 1946, the Secretary of Interior agreed to allow seal hunting to continue within Glacier Bay to alleviate wartime food shortages, but hunting restrictions were imposed. Hunting was limited to Hoonah Natives, hunting seals on land was restricted to within 100 feet of the water, and rifles were not to be carried more than 100 feet inland. Seal hunting permits began to be issued in 1953. In 1955, rifle caliber restrictions were imposed, and two areas of the bay were closed to sealing. Throughout these years, seal hunting was viewed by the NPS as a privilege that was being extended to the Hoonah Tlingit. However, the predominant reaction from Hoonah appears to have been one of bitterness and resentment, stemming from the belief that government officials had granted them something that already belonged to them (Black 1957).

During the early 1950s, the NPS began active management of Glacier Bay, which took the form of establishing a monument headquarters at Bartlett Cove to locate a permanent management staff, park rangers and a Park Superintendent. Tlingit use of the bay decreased substantially in these years, probably due as much to the mere presence of the park authorities as to any official policy developments regarding subsistence hunting or fishing within the bay. Park rangers stationed at Bartlett Cove began more frequent checks of seal hunting parties, however, and occasionally boarded boats to check for permits as they entered the bay.

NPS seal hunting policies changed abruptly in 1965 when a legal opinion was issued by the Department of Interior stating that Indian hunting and fishing rights in the monument had been terminated as a result of the 1959 Tlingit and Haida Jurisdictional Act. This opinion, which differs from other federal interpretations of the Act, provided the legal argument for subsequent gradual efforts to eliminate seal hunting in the bay, leading to several incidents in the late 1960s and early 1970s when seals and weapons were seized by park rangers. The last of these incidents took place in the early 1970s, involving the vessel *New Annie,* and is still viewed by Hoonah residents as being a significant event symbolizing their loss of Glacier Bay.

Complicating NPS efforts to manage seal hunting in Glacier Bay was the fact that in the late 1960s the sale of sealskins grew

profitable and commercial seal hunting, by Natives and non-Natives alike, increased in this period. The Alaska territorial government had placed a bounty on seals in the 1930s as a fisheries protection measure, and for over 25 years, $3.00 was paid for a seal nose. These influences undoubtedly led to seal hunting effort in the bay in excess of what would have resulted from subsistence hunting alone and contributed to the antipathy of park managers toward seal hunting in general. Seal harvest data for the 1950s are unavailable, but an average of 870 seals per year were estimated by the NPS to have been killed within Glacier Bay National Monument in the years from 1961 to 1965 (USDI NPS 1966). In 1972 the passage of the Marine Mammal Protection Act prohibited commercial harvest of seals while allowing continued subsistence hunting by Alaska Natives, and by that time, the park policies prohibiting most subsistence activities were already established.

Subsistence Regulatory Regimes

Nowhere is the rationale or the legal context for NPS policies regarding subsistence uses in Glacier Bay clearly stated. NPS direction appears to be based on interpretation of the National Park Service enabling act and the proclamations establishing the park and expanding it. The decision of the NPS director to allow continued seal hunting and the 1956 Solicitor's opinion regarding the termination of Tlingit and Haida rights to use of the bay also are key elements of this record. While the documentation of decisions made about seal hunting is fairly complete, the sequence of events leading to the termination of other subsistence activities is much less so. The National Park's subsistence policies are significant today in the context of the Alaska National Interest Lands Conservation Act of 1980 (ANILCA) and the state subsistence law. The federal act provides for subsistence uses of the "new" (post-ANILCA) National Parks in Alaska in areas where these activities occurred prior to the passage of the act, but not in the newly designated Glacier Bay National Park (formerly the Monument) since by 1980 subsistence activities had been officially curtailed. The act additionally provides safeguards for future subsistence activities on most federal lands in Alaska, stating that it is the policy of Congress that "...use of the federal lands of Alaska is to cause the least impact possible on rural residents who depend on subsistence uses of the resources of such lands..." (PL 96-487 Title VIII Sec. 802 [1]).

The state subsistence law provides a priority for the harvest of fish and game by residents of rural areas where customary and traditional (subsistence) uses have been found to exist. In implementing this law, the Alaska Board of Fisheries determined in 1989 that residents of Hoonah have subsistence fishing rights in an area that includes Glacier Bay. In the same action, the board provided personal use fishing opportunities in the bay and elsewhere in the region for other Alaskans, including residents of Gustavus, Elfin Cove and Pelican. Because the state has never acknowledged the management authority of the National Park Service over the waters of Glacier Bay, the Department of Fish and Game will issue subsistence fishing permits for the bay to Hoonah residents. The National Park Service maintains that ANILCA does not permit subsistence fishing in Glacier Bay National Park, although subsistence activities by Yakutat residents is permitted in the Glacier Bay Preserve area, near Yakutat.

Such regulatory inconsistencies have in recent years served to highlight the disparity between federal policies and the social and cultural context for Glacier Bay. But whether this credibility gap is closing or widening is unclear, depending on where one looks for evidence. NPS Director William Mott has articulated his intention to find discretion within the law to accommodate the "lifeways" of those who have traditions of use of park lands. At Glacier Bay, great strides have been made, through the Sea Otter Canoe projects, to make Hoonah people and their history more a part of the park management program. At the same time, proposed restrictions on use of traditional commercial and subsistence fishing areas are real threats to the lifeways that Director Mott spoke of, and are likely to unravel whatever ties have been recently established with the Hoonah people.

Discussion

Subsistence uses of Glacier Bay were curtailed by a sequence of events that is poorly understood by the Huna Tlingit. The circumstances that led to the gradual loss of rights to use the land and waters of the National Park have left a legacy of harsh feelings and continued resentment of federal authority. But recent awareness of the implications of ANILCA and the state subsistence law has led many Hoonah residents to seek ways to regain use of Glacier Bay. The 1989 action of the State Board of Fisheries reopens the legal dispute over jurisdiction of marine waters of the park and could lead to a need for clarification of the legal basis for current and historical NPS subsistence policies in Glacier Bay, including the key legal opinion of 1965. Proposed closure of the bay to commercial fishing and closure of traditional use areas to motorized vessels through wilderness classification raises similar jurisdiction issues.

The loss of traditional territory and rights to use that territory is a familiar theme in the emerging Native American tribal histories. In many respects, therefore, the events that have resulted in the Huna Tlingit's loss of rights to Glacier Bay reveal little that is remarkable about government policies toward Native groups except, perhaps, that this history of change and response to change is largely a contemporary one. But in the

Alaska context, the awareness of aboriginal rights and the accommodation of those rights has recently begun to be a working part of public land management. ANILCA provides for subsistence uses of many of the National Parks in the state, and establishes subsistence resource commissions to help resolve management problems related to subsistence.

The application of such a framework to Glacier Bay would be challenging in view of the park's management history and may require amendments to ANILCA, but important management opportunities and benefits would derive. A formal structure involving residents of Hoonah in park management decisions could overcome much of the current distrust of the NPS that is felt in Hoonah. Acknowledgement and interpretation of the cultural context for the park could also be a means of involving the Tlingit residents of Hoonah with park management while enhancing appreciation of the area by park visitors. Even providing for subsistence activities may not depart greatly from current management practices, which currently foster substantial consumptive recreational use of park resources. Spatial and temporal separation of incompatible activities could minimize use conflicts while permitting many traditional activities.

Creative management strategies are needed in order to resolve subsistence issues in Glacier Bay. Due to the history and complexity of these issues, addressing them meaningfully will not be a simple process. However, the consequences of continuing bureaucratic indifference to the issue of the Huna Tlingit subsistence rights may be more problematic in the long run.

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Marine Intertidal Community Development following Glacial Recession in Glacier Bay, Alaska

by

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Abstract

Glacier Bay has recently undergone rapid deglaciation, exposing new substrates to colonization and community development. There is a clearly defined increase in degree of marine rocky intertidal community development with substrate age (0-200 years) and distance (0-90 km) from present-day locations of tidewater glacial termini. Age and distance are almost perfectly linearly correlated. Intertidal species richness increases linearly with increasing distance and age. Near-surface marine environmental factors can be grouped into those that also vary linearly along this gradient (e.g., water temperature, salinity) and those that vary exponentially (e.g., suspended particulate concentration, number of grounded ice fragments). The overall objective of this research was to determine whether the length-of-fjord patterns of intertidal community development in Glacier Bay can be best described by (1) classical long-term biological successional concepts or (2) stresses of the marine physical environment which are themselves controlled by distance from the glacier. Because of the strong autocorrelation of distance and age, a detailed description of intertidal communities and the associated marine physical environment was supplemented by an experimental approach using boulder transplants to determine the relative importance of the two factors.

Results of boulder transplant experiments indicate that primary succession on rocky intertidal substrates occurs rapidly. Bare boulders transplanted simultaneously into the intertidal at six sites along the gradient were rapidly colonized and supported species richness levels similar to those of resident control boulders within three years. At the same time, reciprocal transplants of colonized boulders between near-glacier and baymouth sites showed subsequent mortality and decreased species richness with virtually no recruitment for those transplanted from baymouth to glacier, and accelerated recruitment and increased species richness for those transplanted from glacier to baymouth.

This evidence indicates that the length-of-fjord pattern of marine intertidal community development in Glacier Bay is determined primarily by non-temporal factors related to distance from tidewater glaciers. While time and biotic factors are the major constraints governing the classical succession illustrated so well by Glacier Bay's terrestrial communities, large-scale patterning of marine intertidal communities seems to be governed primarily by strong, non-biologically mediated gradients in the marine physical environment that are in turn controlled by distance from tidewater glaciers. The presence of active tidewater glaciers is extremely important because of the strong physical gradients established by their input of cold, fresh, heavily sediment- and ice-laden water at the heads of inlets.

KEY WORDS: Marine, intertidal, succession, community development, colonization, glacial recession, environmental gradients.

Classical theory of primary succession assumes a major role of time in defining predictable developmental sequences (Odum 1969). Species assemblages change directionally in composition, diversity, and biomass from the earliest pioneering stages to a mature "climax" community that has high resistance to external perturbations. Climax communities typically possess higher diversity and biomass than do early developmental stages.

Glacier Bay ecosystems are ideal for successional research because the area has been exposed by a rapidly receding complex of tidewater glaciers over the past 250 years. This retreat has been well documented, allowing researchers to assign ages accurately to substrate surfaces across a 100 km transect from the baymouth up to the present-day locations of glacial termini. Terrestrial communities present a dramatic display of all stages of succession from the very young,

relatively unvegetated landscape of the extreme upper inlets to the mature, well-developed 250-year-old spruce/hemlock forest adjacent to the fjord entrance. Although studies of terrestrial succession at Glacier Bay have played an important role in the development of successional theory (Cooper 1923; Crocker and Major 1955; Lawrence et al. 1967), virtually no attention has been given to parallel processes of community development in the marine environment.

A preliminary list of species in Glacier Bay intertidal communities (Mueller 1973) suggested that a well-defined gradient in number of species existed along the length of the bay, parallel to the gradient of substrate age (time since initial exposure by the receding tidewater glaciers). In general, number of species tended to decrease with decreasing substrate age. Classical successional theory suggests substrate age as the likely determinant of this observed length-of-fjord pattern. Marine intertidal communities near the glacier, similarly to adjacent terrestrial communities, should exhibit relatively low diversity simply because of short development times, while communities near the mouth of the bay are temporally more mature and hence should be more diverse. Substrate age influences degree of development via initial colonizers beginning the process of facilitation and species replacement with gradual biotically mediated resource enhancement and an increase in diversity.

On the other hand, species richness also follows a parallel gradient of distance from tidewater glacial termini. The species composition of northern marine intertidal communities is known to be affected by salinity (Cimberg 1982) and ice scour (Keser and Larson 1984). Hale and Wright (1979) suggested that these and other environmental factors such as water temperature, water clarity, and suspended sediment content (all of which vary with distance from tidewater glaciers) are important in determining intertidal community composition in Glacier Bay. In general, marine environmental conditions become progressively less oceanic (colder, fresher, more heavily sediment-laden, etc.) with proximity to the glaciers. Presumably, such conditions are more stressful to marine organisms and could inhibit intertidal community development.

Here, then, both age and distance may explain differences in intertidal community development along the chronosequence in Glacier Bay. The problem is to ascertain which effect is more important in controlling the large-scale pattern of community development. Does the pattern represent (a) long-term biological succession or (b) a response to stresses of the marine physical environment which are themselves controlled by distance from tidewater glaciers? Because site ages are known, Glacier Bay provides a unique opportunity to answer this and related questions.

The objective of this study has been to investigate these relationships by (1) quantitatively describing rocky intertidal communities in Glacier Bay and associated physical factors of the ambient marine environment and (2) conducting a series of experimental manipulations of intertidal substrates. This approach should increase our general understanding of the primary controls over large-scale patterns of community development in the Glacier Bay intertidal, allowing a general comparison with community development processes operating in the adjacent terrestrial environment.

Physical Environment

The intertidal zone in Glacier Bay is defined spatially by the vertical tidal excursion which can approach 8 m on spring tides. During the summer of 1984, water temperature, salinity, and total suspended particulates at depths of 0, 2.5, 5, and 7.5 m were measured at each of 40 sites from Pt. Gustavus to Muir Glacier (Fig. 1). Samples were collected just offshore from each intertidal site, and sites were chosen so that they were as similar as possible in terms of rock type, beach slope, exposure to wavewash, and proximity to freshwater streams. Since light availability could contribute to the distributions of intertidal algae, water column light attenuation was measured with a submersible light meter by taking readings at every m from the surface to 8 m. Turbidity was expressed as a vertical extinction coefficient. Ice scour was measured in terms of number of grounded ice fragments along a 100-m section of shoreline at each site. All measurements were made during the same period of the tidal cycle, generally the three hours immediately following low tide. In addition, time since initial exposure was calculated for each site using known terminus locations from the historical record (Powell 1984).

Substrate age increased linearly ($r^2 = 0.99$; $p < .001$) with distance from the present-day terminus of Muir Glacier (Fig. 2). Consequently, biological and physical parameters were as well correlated with distance from the glacier as with substrate age. Except for occasional short periods of very rapid retreat, the overall rate of glacial recession (approximately 2.3 km/year) has been remarkably constant.

The other physical environmental parameters can be grouped into those that also varied linearly along the distance/age gradient and those that varied exponentially. Water temperature and salinity increased linearly with distance and age from glacier to baymouth (Figs. 3a,b). In contrast, amount of suspended particulates, extinction coefficient, and number of grounded ice fragments decreased exponentially along the gradient, with the greatest change occurring across the 20 km closest to the glacier (Figs. 3c-e). These data were consistent with the relatively few published studies of the physical environment of tidewater glacial fjords (Syvitski et al. 1987).

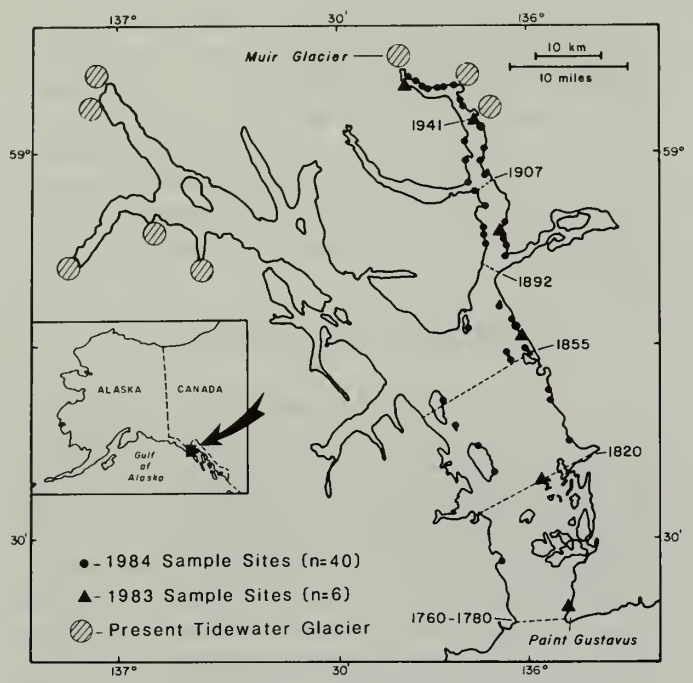

Fig. 1. Glacier Bay, Alaska, showing locations of historical and present tidewater glacial termini, 40 1984 descriptive study sites, and 6 1983 boulder transplant sites.

Biological Community

Quadrat data was used to describe the intertidal biological community at each site during low tide at standard vertical heights of 0, 1.25, 2.5, 3.75, and 5 m above mean lower low water. Quadrat data included percent substrate coverage for each species of intertidal plant and animal. Abundance was recorded for rare or mobile animal species. Intertidal substrates were all consolidated bedrock exposures.

Aspects of the biological community exhibited clear distance and/or substrate age-related trends in both community composition and species richness. Some species occurred along the entire chronosequence, but others, which were common in the outer bay, gradually disappeared with decreasing distance from the glacier (Fig. 4). Species richness (mean number of species encountered per quadrat) increased linearly with increasing distance from the glacier and substrate age (Fig. 5). Because of the close linear relationship between substrate age and distance from the glacier, correlation analyses cannot separate the relative importance of these two factors in determining biological community composition. Statistically, they must be considered equal. Stepwise multiple regression analyses for each species (using either percent coverage or abundance) at each intertidal height vs. all environmental parameters showed that approximately half of the species at each vertical level were not significantly correlated with any environmental variable (critical F = 4.000). Nevertheless, the distance/age factor was most frequently identified as the parameter that best predicted or statistically "explained" the distributions of most of the remaining species. Other important environmental parameters were water temperature, salinity, and suspended particulate nitrogen, all of which were linearly related to distance and age. Exponentially varying factors such as total suspended particulates or number of grounded ice fragments do not appear to be important determinants of the large-scale pattern of intertidal community development, although they may be significant in early succession or at spatial scales in close proximity to glaciers. Directional and predictable temporal patterns of species replacement occur in marine intertidal communities, just as they do in terrestrial ones. However, it is unlikely that substrate age alone controls degree of intertidal community development across the entire 200-year chronosequence in Glacier Bay. Experimental and descriptive studies of marine succession from totally bare rocky intertidal surfaces to fully developed "mature" communities indicate a much shorter time for development, generally five to ten years (Southward and Southward 1978; Sousa 1979). This suggests that the physical environment is very important in controlling the pattern of development in Glacier Bay.

One way to separate age and distance effects is to employ an experimental approach whereby both substrate age and proximity to the glacier are manipulated so that their effects can be separated from one another.

Bare Boulder Transplants: Manipulation of Substrate Age

In August 1983, uncolonized boulders from well above the vertical extent of high tides were transplanted into the intertidal zone at six boulder beach sites evenly spaced along

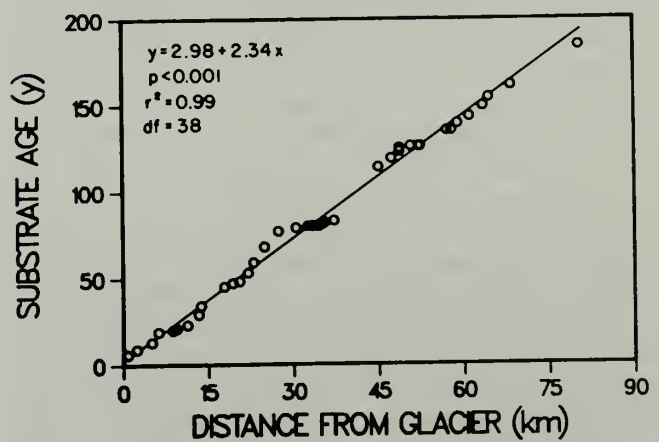

Fig. 2. Relationship of substrate age to distance from Muir Glacier for the 40 1984 study sites.

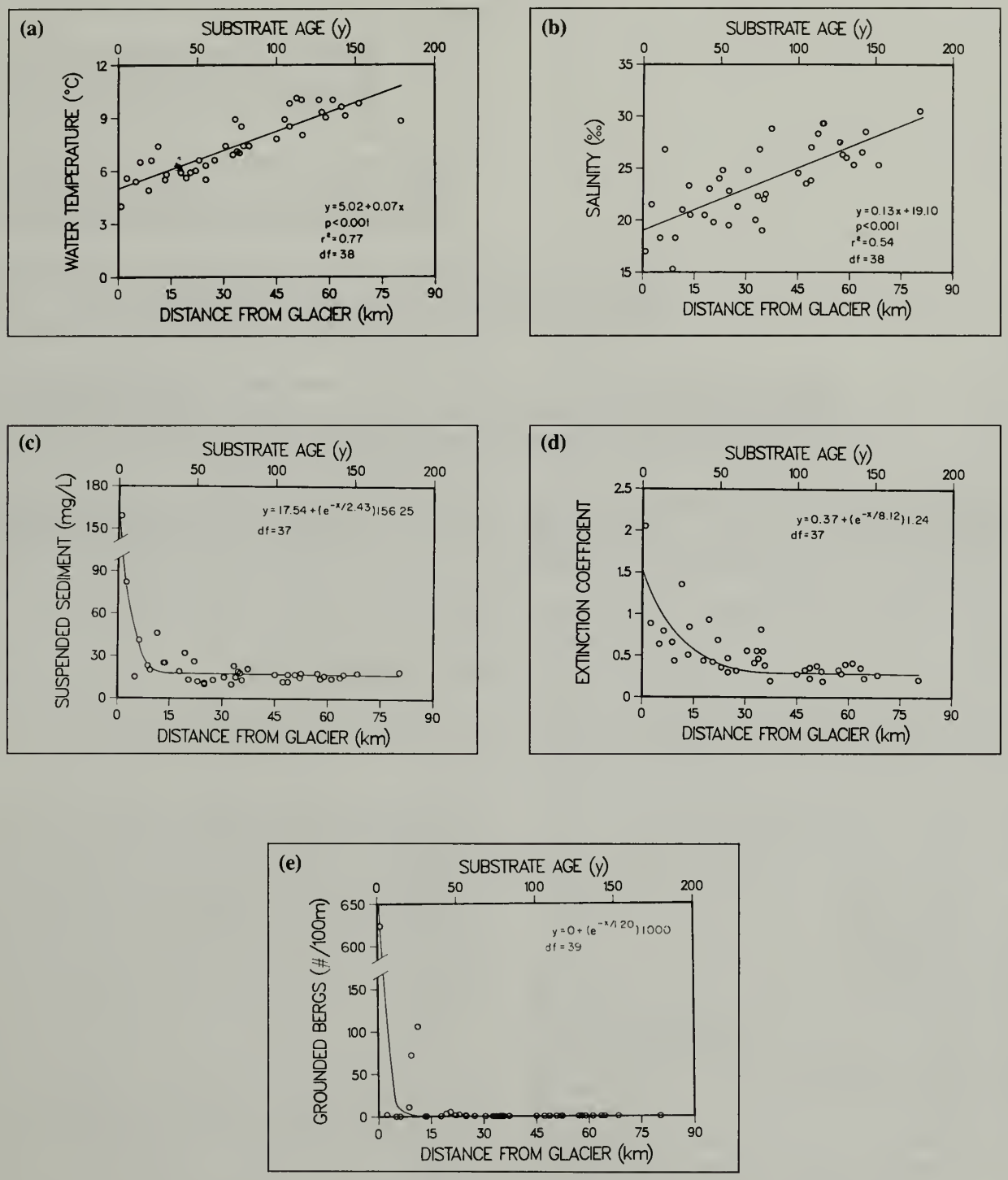

Fig. 3. Relationships to distance from Muir Glacier and substrate age shown by near-surface (a) water temperature, (b) salinity, (c) total suspended particulate concentration, (d) extinction coefficient, and (e) number of grounded ice fragments (= bergs). Values in (a), (b), and (c) are means of measurements made at depths of 0, 2.5, 5, and 7.5 m. N = 40 sites.

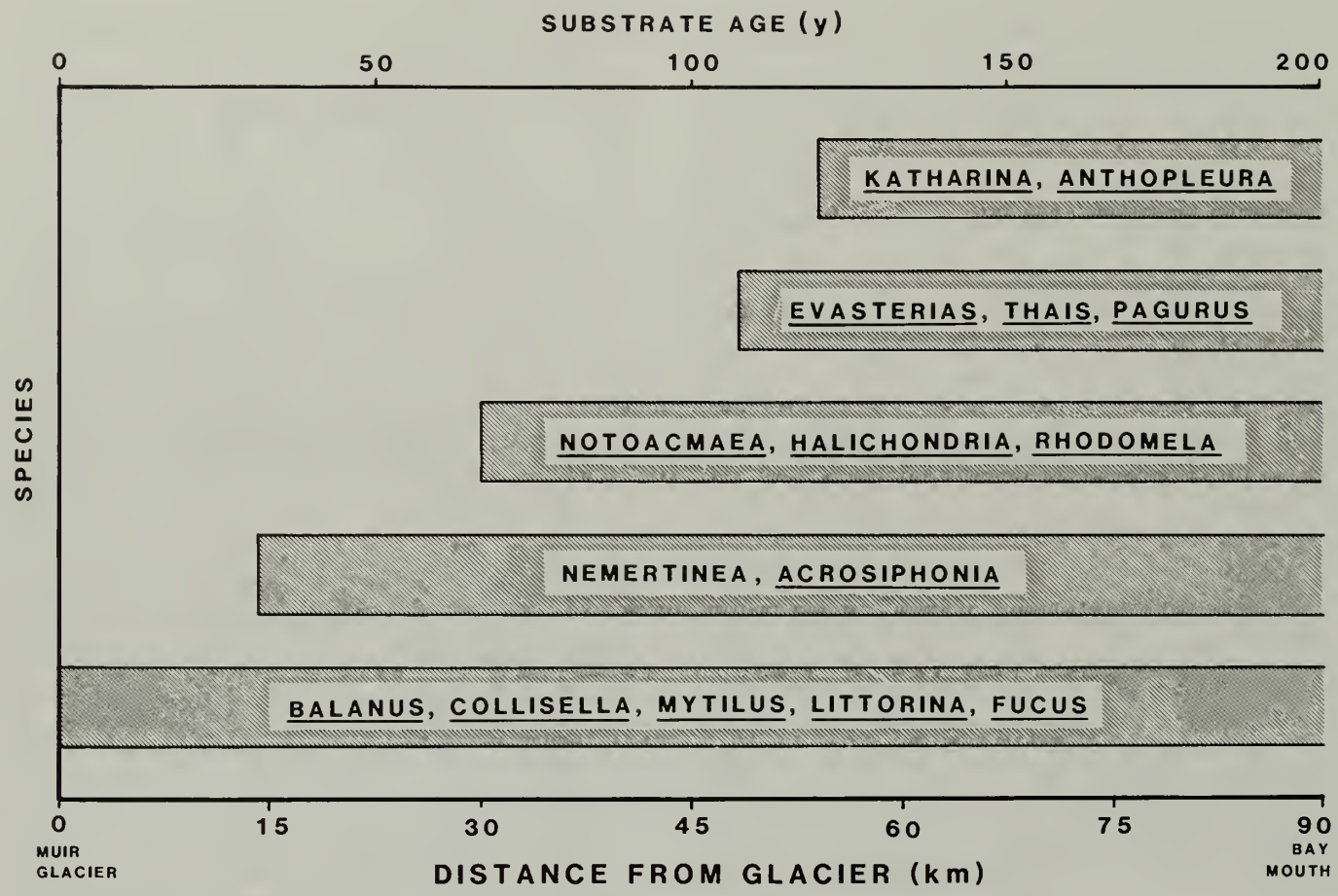

Fig. 4. Approximate maximum extents of distribution toward Muir Glacier of major intertidal organisms in Glacier Bay.

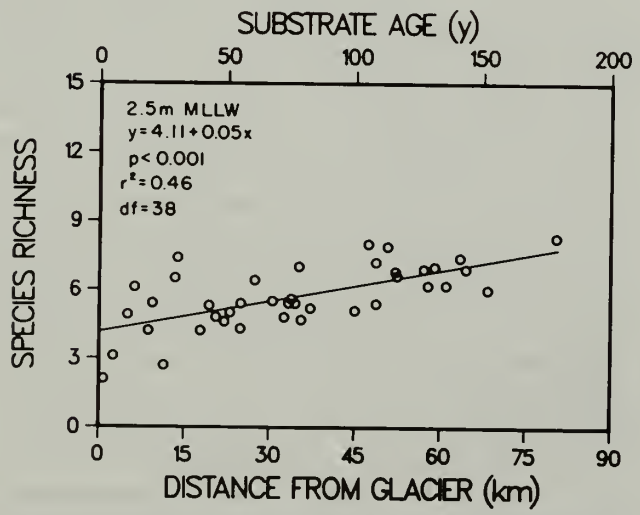

Fig. 5. Relationship of intertidal species richness (mean number of species per quadrat) to distance from Muir Glacier and substrate age at the 2.5 m vertical intertidal level. N = 40 sites.

the length-of-bay transect from the baymouth to within 2 km of the Muir Glacier terminus (Fig. 1). These boulders were subsequently relocated twice each year, early summer (May-June) and late summer (August-September) for three years. On each visit, the developing biological communities on these experimental boulders were quantitatively described using quadrat data. Also on those visits, communities of neighboring resident control boulders were described.

This experiment allowed the introduction of substrates of the same age (0 years) to sites of varying distance from the glacier. If communities at all sites developed at the same rates and to the same degrees regardless of relative proximity to the glacier, it would strongly suggest that substrate age is very important in controlling the overall pattern of degree of intertidal community development in Glacier Bay. If, on the other hand, bare boulders close to the glacier developed more slowly or to a lesser degree than those farther from the glacier, it would suggest that distance from the glacier and environmental parameters mediated thereby are the critical factors.

Results were mixed. As expected, species richness for control boulders generally increased from glacier to baymouth on all visits. At each site, overall species richness remained quite stable over the three-year course of the experiment but typically increased from early summer to late summer each year and then decreased between late summer and the following spring. This was not an unexpected result and can be observed in adjacent terrestrial communities as annual species appear and perennials become increasingly apparent through the summer growing season, only to die back in the fall.

The pattern of change was different for the bare boulder transplants. As expected, they immediately began to support colonization and underwent most of the total development observed over the entire experiment during the initial year. There are three interesting observations relating to the development of these experimental communities. First, in contrast to the controls, species richness increased throughout the experiment and did not show seasonal responses. Secondly, at the end of the experiment the mean level of species richness among experimental boulders showed a pattern similar to that of the controls, increasing from glacier to baymouth. Thirdly, by the end of three years, the transplant boulders supported communities equal in species richness to those of their neighboring resident control boulders.

In early succession, rapid colonization of intertidal substrates occurs, and community development quickly progresses to the level supported by previously colonized surfaces. At any given site along the chronosequence, biological development of uncolonized substrates proceeds over the first three years with minor seasonal variations compared to resident communities that apparently have already "matured" to the extent allowed by the environments of their sites. Communities on even-aged substrates do not develop to the same degree independently of distance from the glacier.

It is possible that the differing degrees of community development on experimental boulders observed across sites were merely the result of recolonization of new substrates amid communities that are indeed ultimately constrained in their development by age. This is difficult to test conclusively because it is impossible to transplant entire sections of beach from one location to another. It is possible, however, to transplant small community units—colonized boulders—between locations.

Reciprocal Boulder Transplants: Manipulation of Glacial Proximity

At the same time that the bare boulder transplant experiment was initiated in August 1983, resident colonized boulders from the intertidal zone were transplanted reciprocally between the two extreme sites near Muir Glacier and Pt. Gustavus (Fig. 1). These boulders and their neighboring controls were revisited and described on the same schedule and using the same methods as for the bare transplant experiment.

In this experiment, distance from the glacier was the factor being manipulated. If proximity to the glacier is not an important controlling factor, then relocating boulders of different ages between the two sites should not significantly affect the degree of development of their communities. If, however, the relatively well-developed communities from the baymouth decreased in degree of development after being transferred to the near-glacier site and vice versa for communities originating near the glacier, then it would indicate that distance from the glacier and environmental factors related to distance are important. The potential for transplant shock was minimized to the greatest possible extent—boulders removed from a site at low tide were transplanted back into the intertidal at the other site, nearly 90 km away, approximately twelve hours later during the following low tide.

Biological communities of resident control boulders from the two sites remained fairly constant in species richness over the three years of the experiment, although at a significantly lower level at the near-glacier site than at the baymouth site. Communities of the reciprocally transplanted experimental boulders, however, showed significant responses to their new environments.

Boulder communities transplanted from the baymouth site to the near-glacier site responded by rapidly decreasing in species richness over the first winter. Subsequently there was some further mortality, but the most significant decrease occurred during the first year, and species richness had stabilized to a level matching that of the resident control boulders by the end of the experiment. Transplant boulder communities were initially dominated by barnacles, the common rockweed *Fucus distichus*, and littorine snails, with a mean total surface coverage of approximately 40 percent. After three years at the near-glacier site, only a few adult barnacles remained, some space became occupied by a thin algal coating of benthic diatoms, and the mean total coverage was less than 10 percent.

Boulder communities transplanted in the opposite direction from glacier to baymouth also rapidly assumed the level of species richness equal to that of the local controls, in this case significantly increasing in number of species during the first year of the experiment. These boulders behaved essentially like the bare boulders that were newly transplanted into the intertidal at the Pt. Gustavus site. Boulder communities from the near-glacier site initially consisted of the benthic diatom coating and rare adult barnacles, with a mean total surface coverage of less than ten percent. Within three years following the transplant, however, coverage more than doubled, and boulders were colonized by littorine snails, limpets, Fucus, and other macroalgae. Again, transplants moved in both directions appeared to have stabilized in species richness by the end of the three-year experiment. Results from this reciprocal transplant experiment provide strong evidence that distance

from the glacier is a very important factor controlling the large scale pattern of intertidal community development in Glacier Bay, probably through the influence of glacially mediated physical environmental parameters. Specifically, the two most significant observations were (1) the rapid and large biological responses to new environments at opposite ends of steep physical gradients and (2) the subsequent stabilization of species richness at levels equal to those of the surrounding communities within three years.

Conclusions

Together these descriptive and experimental results have yielded valuable insights into the control of intertidal community development in Glacier Bay. Primary succession occurs very rapidly on rocky intertidal substrates. "Mature" communities develop in less than five years on initially bare surfaces and during this time succession strongly affects community composition and structure. The long-term, large-scale spatial pattern of intertidal development seen in Glacier Bay, however, results primarily from response to non-temporal factors related to distance from tidewater glaciers. These distance-related factors are likely experienced as physiological gradients by marine intertidal organisms. Time certainly is important in the very short term, but the overall length-of-fjord pattern of marine system development reflects fundamentally different control processes from those in the adjacent terrestrial system. While Glacier Bay's terrestrial communities exhibit classical long-term successional development under the major constraints of time and biological control, the large-scale patterning of marine intertidal communities seems to be governed primarily by steep, abiotically mediated gradients controlled by distance from tidewater glaciers. Active tidewater glaciers are extremely important because of the strong physical gradients established by their input of cold, fresh, heavily sediment- and ice-laden water at the heads of inlets. The overwhelming importance of the physical environment (vs. biotic processes) in controlling aquatic community development in Glacier Bay appears to extend beyond the marine system to include freshwater streams, at least in their early stages (Milner 1987).

Much work remains to be done to identify which environmental parameters are most important in governing intertidal community development, as well as the mechanisms of their control. In 1987, a further boulder transplant experiment was initiated. This experiment involves bare boulder transplants and reciprocal transplants of colonized boulders between intertidal sites near and far from a freshwater stream in lower Glacier Bay to better understand effects of water temperature and salinity. It appears that indirect effects of predator exclusion may be very important at these sites.

Also in 1987, a larval dispersal/recruitment study was begun in order to evaluate the contribution of early life history stages to community development patterns. Surface plankton samples were collected biweekly throughout the summer at the six transplant sites so that relative up-fjord dispersal abilities of the propagules of intertidal organisms could be assessed. Preliminary analyses of a few of these samples suggest that both species richness and abundance of intertidal larvae follow a pattern of increase with increasing distance from the glacier. Those collections were continued during the summer of 1988.

In the early spring of 1988, intertidal settling plates were installed and monitored at the six transplant sites. Resulting settlement and establishment data combined with the plankton data and the findings of the earlier bare boulder transplant experiments should add substantially to our understanding of the physical gradient controls over dispersal, settlement, and establishment.

Levels of physiological "health" and relative growth rates of one intertidal plant and one intertidal animal will be examined through other work conducted in 1988. Photosynthetic rates of the common rockweed *Fucus distichus*, which occurs along the entire baymouth to glacier gradient, were measured at four of the six sites. Growth rate data were also collected at all six sites from plants marked and measured in spring and relocated in late summer. Preliminary analyses suggest no significant difference either in photosynthetic rate or growth rate among plants at different locations. Adult intertidal barnacles (*Balanus balanoides*, *B. glandula*, and/or *B. cariosus*) were collected from the six sites for age and growth rate determinations. These analyses have not been completed. Additional collection of adult brooding barnacles at all six sites is tentatively planned for February 1990 just prior to release of larvae. This should allow a straightforward comparison of relative fecundity levels among locations.

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Community Development in a Glacial Stream

by

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Abstract

Different stages in the chronological sequence of aquatic community development may be found in Glacier Bay. Post-glacial colonization and ecological development has been investigated over a ten-year period in a number of recently established streams. Of particular interest is Wolf Creek, a newly emergent stream arising as meltwater from a receding remnant glacier. Studies from 1977 to 1979 indicated that the colonizing species of this stream were all representatives of the Chironomidae (non-biting midges), which exhibited significant associations with filamentous algae. Although these species have been recorded as inhabitants of glacial streams elsewhere, densities have been typically low. However, densities in Wolf Creek exceeded 18,000 individuals /m^2. Samples collected in 1986 showed that the developing communities now included representatives of the Ephemeroptera (mayflies) and Plecoptera (stoneflies). These additions to the fauna are attributed to time for colonization rather than physical changes in habitat. Future pathways along which the stream community will develop will probably depend upon the characteristics of clearwater runoff into the system, the continued presence of a lake within the system, and the extent of riparian vegetation development.

KEY WORDS: Streams, colonization, succession, community development, aquatic insects.

The variation and extent of ice recession that has occurred in Glacier Bay National Park provides unique opportunities to examine colonization by freshwater organisms of emergent stream systems of differing ages. Stream age is reflected by the distance from the retreating glacier termini, and thus, temporal changes in community structure can be studied on the basis of spatial differences. Studies have shown that the overall pattern of stream development in Glacier Bay is controlled principally by abiotic factors, particularly flow and sedimentation effects (Milner 1987; Milner and Bailey 1989). Following glacial recession, the retention of a lake within the watershed to buffer flow variations and to settle coarser sediment is of critical importance to the biological community. However, within this pattern of physically dominated long-term stream changes, communities within a stream may on the shorter term be influenced by the colonization dynamics of immigrating species and interactions between these species.

Information on community development in streams through primary successional processes is scarce. Primary succession in streams occurs after a disturbance severe enough to remove the previous community such that no organic matter remains to establish an energy base for community development (Gore and Milner in press). Gore (1979, 1982) examined community development in a reclaimed river channel after strip mining and found that maximum densities of macroinvertebrates were found in less than 90 days and species equilibrum in about 200 days, while Minshall et al. (1983) found after a major flood maximum densities within 400 days and species equilibrium between 600 and 650 days. Both these studies possessed upstream sources of colonizers. The eruption of Mt. St. Helens destroyed several drainages near the blast zone; two years after the event, few aquatic invertebrates had invaded these denuded streams, and after five years, caddis fly larvae were still uncommon (Anderson and Wisseman 1987).

This paper focuses on community development in one stream, Wolf Creek, from 1977 to 1986 and includes reference to a new clearwater stream, Nunatak Creek, to indicate how it may develop in the future. Wolf Creek, 3.6 km long, is a first order stream that orginates from a meltwater lake near the southeast edge of Muir Remnant in upper Muir Inlet and flows initially through bedrock and then over unconsolidated glacial deposits. Although the mouth of this stream was uncovered in the late 1940s, the study reach was deglaciated approximately between 1955 and 1960 (Fig. 1). Temperatures of 2-3°C and turbidities between 140 and 150 NTU were encountered in Wolf Creek at all sampling periods.

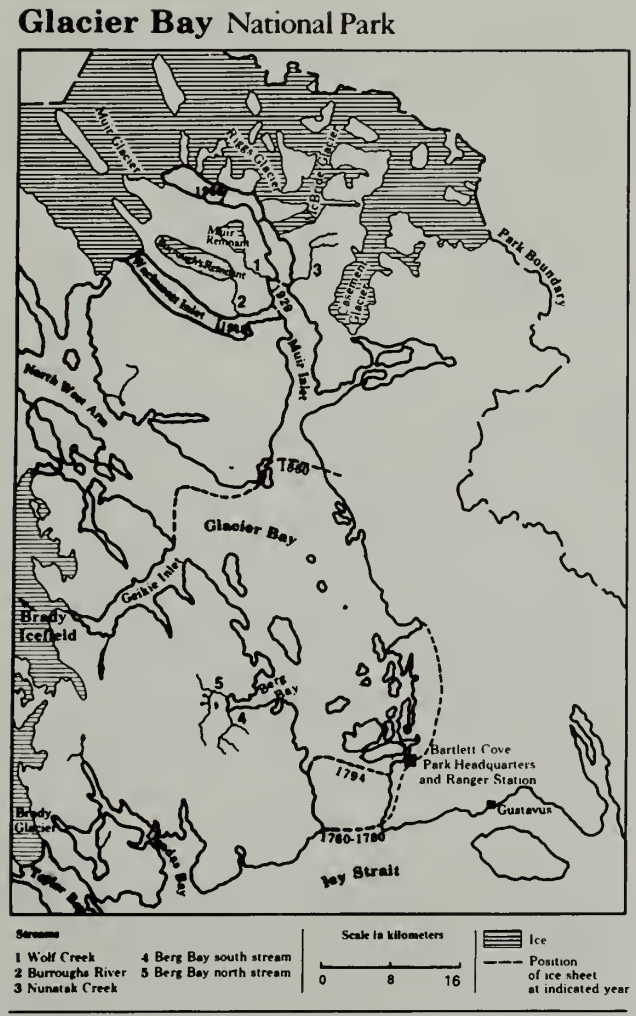

Fig. 1. Map showing location of study streams (after Milner 1987).

Methods

Macroinvertebrate samples were taken at a representative 15-m sampling station. In August 1978, the 15-m section was marked out and subdivided into fifteen 1-m strata. From each strata, four stones were removed as determined by random coordinates and carefully placed in a standard pond net held downstream of the stone. Each stone was thoroughly hand-picked of invertebrates which were preserved in 70 percent ethanol. In 1986, samples were taken by a portable invertebrate sampler with a 380-micron mesh net on a bimonthly basis. Five samples were taken using random coordinates at each sampling period and again preserved in ethanol. Samples were sorted and identified to the lowest taxa possible.

Results

Chironomidae (Diptera) were the pioneer colonizers of Wolf Creek, with five species being found in 1978. Total numbers exceeded 140 individuals/150 cm² of stone surface (approximately 16,800/m²) (Fig. 2). The chironomid larvae displayed positive associations with filamentous algal growth using a modified Chi squared test. In June and August of 1986, total numbers of macroinvertebrates were 5,151/m² and 4,193/m², respectively, and species diversity had increased with the inclusion of representatives of Ephemeroptera (mayflies) and Plecoptera (stoneflies) (Fig. 3).

To measure the persistence of a given stream community, it is necessary to measure its composition on at least two occasions far enough apart for complete population turnovers to have occurred (Connell and Sousa 1983). Persistence in species composition is high when community structure changes little in terms of the presence or absence of species. A measure of persistence can indicate temporal influences in the development of stream communities. One approach is to calculate Jaccard's Index (JACC) (Southwood 1978) for the complete species pool, where:

$$\text{JACC} = \frac{j}{a+b-j}$$

JACC was calculated for Wolf Creek to compare the species composition of the community in August of 1978 and August

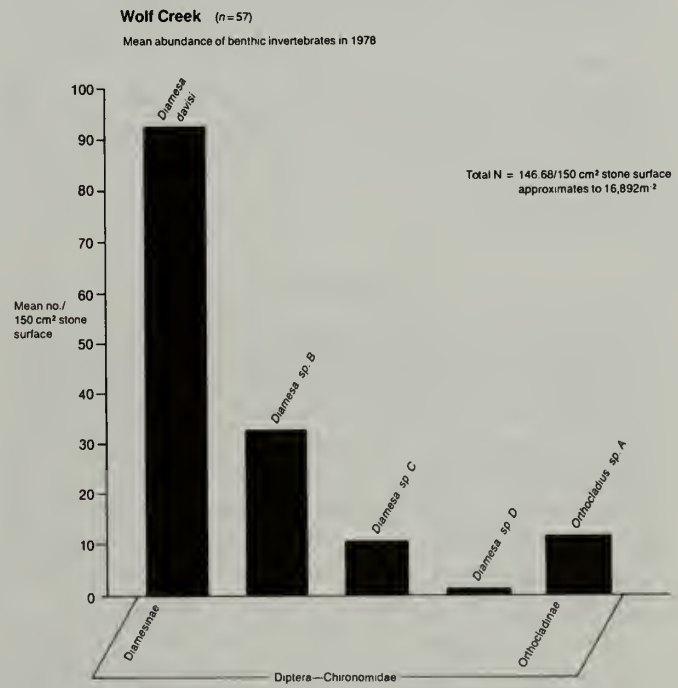

Fig. 2. Mean abundance of benthic invertebrates in 1978 from the representative sampling site in Wolf Creek.

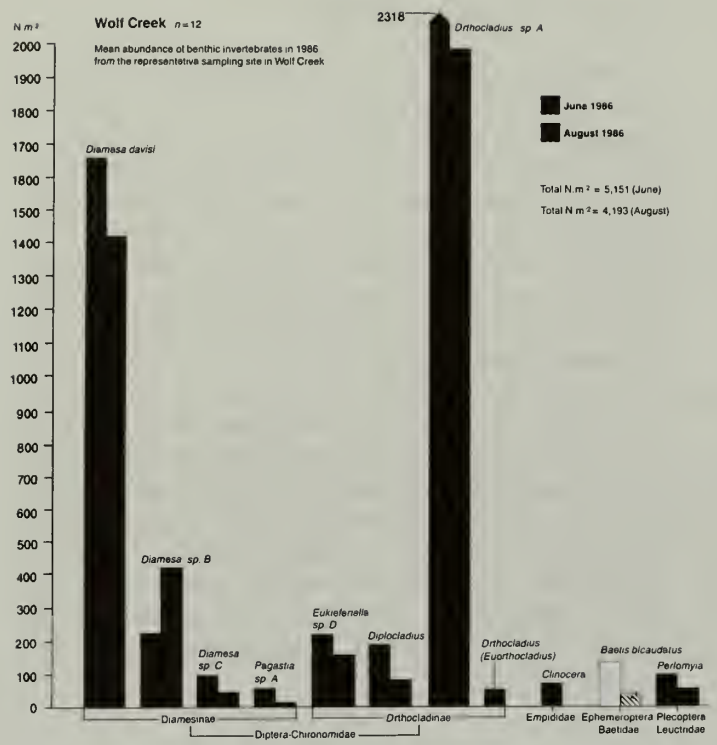

Fig. 3. Mean abundance of benthic invertebrates in 1986 from the representative sampling site in Wolf Creek.

of 1986, where a = number of taxa in the community in 1978, b = number of taxa in the community in 1986, and j = the number of taxa found in both 1978 and 1986. Jaccard's Index can assume values from 0 (no similarity) to 1 (identical). The value for Wolf Creek was 0.33. However, the JACC calculated to compare Wolf Creek in 1986 and Nunatak Creek in 1978 (Fig. 4) was 0.47.

Discussion

Four main sources of colonization of freshwater habitats were identified by Williams and Hynes (1976), namely: downstream drift, upstream migration within the water, vertical upward migration from within the substrate, and aerial sources. With cataclysmic disturbances such as glacier movements and the formation of an entirely new stream channel, without upstream or downstream colonization sources, aerial dispersal is the initial mechanism of colonization. Drift may become more important as the community becomes established.

With aerial dispersal the principal route, most insects have an advantage over non-insect forms in possessing a winged terrestrial stage. Indeed, in 12 years of study, no non-insect forms have colonized Wolf Creek. Chironomids, being small winged and relatively light, have a high passive dispersal ability and are typical first colonizers. Other authors have suggested that the large standing crop of periphyton that frequently occurs following major disturbances, combined with the reduction of predators and competitors, creates ideal conditions for the rapid expansion of chironomid populations (Yasuno et al. 1982). Indeed, the absence of predators probably accounts for the extremely high densities observed in 1978.

An examination of stream channel development has shown that channel changes in Wolf Creek were slight from year to year, mostly related to minor erosion and deposition of silt released from the remnant glacier (Sidle and Milner, this volume). Larger sediment particles are settled in the meltwater lake, and the major loading to these streams is fine silts and clays (< 0.002 mm) which, at most stages of flow, are transported out of the system in suspension. The lake also acts to buffer discharge variations causing relatively stable flows. Thus, the detrimental effects of sediment deposition and flow variations on macroinvertebrate densities observed in Nunatak Creek (Milner 1987) are ameliorated in Wolf Creek. Other parameters, notably temperature and turbidity, did not change from 1978 to 1986.

Communities that show little tendency to persist may be influenced more by stochastic processes, with species abundance and composition the result of unpredictable abiotic changes rather than that of deterministic, biological changes (Townsend et al. 1987). The physical factors that dominate overall stream development on the longer temporal scale have not changed significantly from 1978 to 1986. Ward and Stanford (1979) consider temperature and discharge the most useful variables as a measure of environmental variability.

Hence, the lack of persistence in Wolf Creek is probably attributable to dispersal and colonization by additional species as a result of a greater length of time for stream development. Within an apparent constant environment, deterministic biological interactions become more important, for example

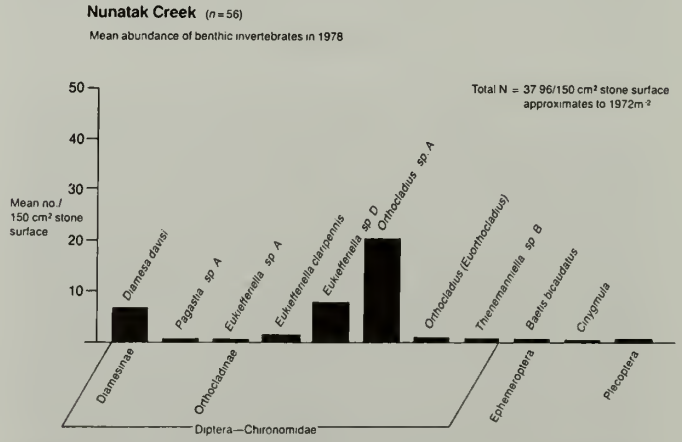

Fig. 4. Mean abundance of benthic invertebrates in 1978 from the representative sampling site in Nunatak Creek.

predation and competition. With the presence of a predatory stonefly, densities of the chironomids were significantly lower in 1986. In addition, the species composition of the chironomids had changed dramatically between 1977 and 1986. One of the first colonizers, *Diamesa sp.* B *(sommermanni)* had disappeared, and the Diamesa davisi group was no longer dominant. *Orthcladius sp.* A had become the most abundant chironomid, and the overall diversity of chironomids had increased. It will be interesting to observe how the colonization of Wolf Creek by Dolly Varden *(Salvelinus malma)* in 1988 will further influence the community structure as they predate on the benthic fauna.

Nunatak Creek, 5 km distant on the east side of Muir Inlet, is a new clearwater stream which had ice in its watershed until 1965. It probably provides an indication of how Wolf Creek will develop once the remnant ice has completely ablated. Indeed, the fauna of Wolf Creek in 1986 more closely resembles that of Nunatak Creek in 1978 than Wolf Creek in the same year.

In addition, it is evident that species equilibrium (immigration = extinction) has still not been reached in Wolf Creek after 12 years of study. This exceeds previously recorded time intervals for streams being colonized within a primary successional framework.

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Benthic, Epibenthic and Planktonic Invertebrates in Ice-proximal Glacimarine Environs: Life in the Turbidity Lane

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Abstract

In 1984 and 1986, benthic, epibenthic and planktonic invertebrates were sampled incidentally during intensive studies of tidewater sedimentation processes proximal to McBride and Riggs Glaciers, on the east side of Muir Inlet in Glacier Bay. Organisms were found to occur throughout ice-proximal areas in remarkably high densities, averaging 21.7 $\times 10^4/m^2$. Although no consistent pattern to the density distribution within the McBride Inlet existed, highest faunal densities ($11.4 \times 10^6/m^2$) occurred closest to the meltwater upwelling from a subglacial stream. Benthic and epibenthic harpacticoid copepods, copepod larvae and benthic nematodes predominated, although pelagic calanoid copepods were also prominent in several samples.

Near-bottom sediment trap and vertically-stratified zooplankton samples were collected to determine whether benthic meiofauna originate from the glacial outwash plume. While abundant in the sediment trap samples, harpacticoids were rare in the low-salinity surface waters, suggesting that these organisms are probably well established benthic/epibenthic populations rather than "fallout" from the meltwater plume. Calanoid copepods, which also occurred in the sediment traps, were prominent in subsurface fjord water advected into the McBride Inlet, implying that these organisms are drawn into the McBride Inlet from Muir Inlet via circulation driven by tidal currents and barotropic flow created by the upwelling meltwater stream at McBride Glacier. At the interface with this rapid, low-salinity current, they may be "stripped" from the current as a result of the high sediment particle flux within 500 m of the glacier.

These results pose interesting questions related to the ability of such dense "pioneer" harpacticoid copepod assemblages to colonize and persist in a dynamic benthic environment, and of the potential source and magnitude of organic matter, including pelagic zooplankton, which sustain these populations. Further research to address these questions would provide insight to the processes regulating benthic ecosystem succession of the biota in Glacier Bay.

KEY WORDS: Tidewater glaciers, benthic/epibenthic meiofauna, zooplankton, fjord benthos, glacial sedimentation.

Studies of ice-proximal glacimarine sedimentation processes in Muir Inlet over the past four years have vastly increased our understanding of the processes of circulation and sedimentation which take place at the front of tidewater glaciers (Cowan, this volume; J. Duncker, N. Illinois Univ., pers. comm.). These investigations have, in essence, begun to

clarify inferences from the marine sedimentary record of the retreat of tidewater glaciers over 90 km along Glacier Bay (Powell 1981, 1984, this volume). Dynamic interactions between the glaciers' influent meltwater streams and tidal circulation in the fjord are the principal determinants of the distribution and structure of the glacially derived sediments which are mostly deposited within one or two km of the glacial margin (Cowan 1988, this volume). The force in this process is the sediment-laden meltwater plume which, rising at the face of the glacier, forms surface "overflow" (and, rarely, subsurface "interflow") currents with potentially high velocities (10-25 cm/s). The result is a temporally and spatially variable, high (~ 1 cm/d) flux of sedimentary particles (glacial rock flour, silt and sand) from these currents to the benthic habitat recently uncovered by the glacier.

As these studies unfolded, an interesting question evolved: that of the ability of benthic and epibenthic animals to colonize and persist in the ice-proximal bottom sediments under this high sedimentation rate, and a probable deficiency of either living (phytoplankton) or non-living (detrital) organic matter. If such processes measurably affect the rate and pattern of benthic/epibenthic community development in the proximity of receding tidewater glaciers, a better understanding of this glacier-fjord coupling would tell us much about the "evolution" of the Glacier Bay ecosystem as it unfolded from its Neoglacial state.

As a part of the ongoing studies of circulation and sedimentation processes at McBride and Riggs Glaciers, we conducted preliminary sampling of the fauna associated with ice-proximal bottom sediments, meltwater plume, and fjord waters. The objective was to determine if fauna exists in this dynamic habitat and, if established populations were found, to explain their origin and production.

Methods

Twenty-seven 15.2 x 15.2 cm Ekman benthic box corer samples collected in front of McBride and Riggs Glaciers during June and July 1984 were subsampled for macroinvertebrates and meiofauna. When each box corer was opened, a 3-cm I.D. PVC plastic corer was pushed 10 cm into the exposed sediments, preferably through an area with overlying surface water. This core was capped at both ends and the contents transferred to a sample jar and preserved by adding sufficient buffered formalin to make a 5% preservative solution. In the laboratory, these subsamples were sieved through 0.150-mm mesh to remove fine sediment particles and panned to separate meiofauna and small macrofauna from larger sediment particles. Preliminary sorting and enumeration was performed under a stereo zoom, binocular dissecting microscope. Based on the results of this preliminary analysis, representative subsamples were further examined for species and life history composition; these samples were selected as those with the most individuals and most meiofauna diversity from different regions of the inlet in front of the McBride Glacier.

In summer 1986, during more detailed studies of the circulation and sedimentation in McBride Inlet, supplemental samples were retained from sediment traps and zooplankton net collections were made at two stations in McBride Inlet (Fig. 1). All samples were collected under "deep water renewal" circulation patterns occurring during June and July (Fig. 2). Sediment traps were 4.5-cm x 15-cm polyethylene tubes attached to fixed nylon lines suspended between 5 m and 10 m above the bottom and deployed for between 8.1 and 93.5 h. A 15.2-cm diameter ring plankton net with 0.243-mm mesh was used to collect zooplankton in near-bottom and surface (overflow) waters over 0.8 to 3.8 h (e.g., within a tidal cycle).

All biological samples were preserved as in the benthic core study. Sediment trap meiofauna abundance and biomass were standardized according to independent estimates of the total sedimentation rate (mg/cm^2) for each trap; water volumes sampled during zooplankton net deployments were crudely approximated using estimates of the velocity (cm/s) at the specific sampling depths.

The collections were facilitated by the assistance of Ellen Cowen, Jim Duncker and Drew Phillips, Northern Illinois University; Jeff Cordell, Fisheries Research Institute, completed taxonomic identifications of the copepod fauna.

Results

Meiofauna and small macrofauna were surprisingly prominent components of the benthic sediment samples collected in McBride Inlet (Table 1). Total densities (excluding eggs) averaged 21.7 $\pm$ 26.3 x 10^4 organisms/m^2, with a maximum of 11.4 x 10^6/m^2 (Fig. 3). While meiofauna and small macrofauna assemblages in fjords have not been studied extensively, the densities found in McBride Inlet are within the range or exceed those found in two northeastern Pacific fjords, northern Howe Sound (4 to 13 x 10^5) and Trevor Channel (29.2 to 17.7 x 10^5), which have not had ice-proximal glacimarine conditions since the later Holocene (Marcotte 1980; Heusser et al. 1985).

Crustaceans, particularly harpacticoid copepods, dominated the samples; densities of late stage copepodid and adult harpacticoids averaged 8.7 $\pm$ 16.0 x 10^4 individuals/m^2, followed by copepod naulpii and early stage copepodids (5.0 $\pm$ 7.7 x 10^4/m^2); densities for both these categories exceeded 1 x 10^5/m^2 at six sampling sites; densities of ovigerous female harpacticoids averaged 9.6 $\pm$ 18.4 x 10^4/m^2. Other benthic

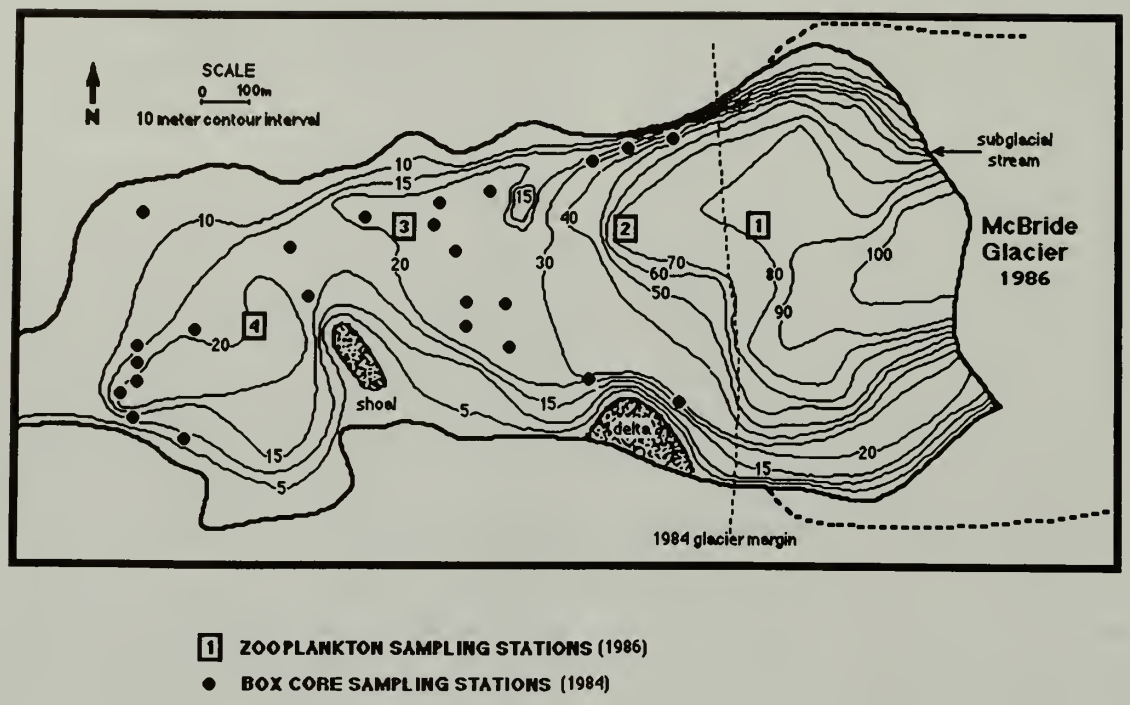

Fig. 1. Location in McBride Inlet of benthic core samples collected in 1984 and sediment trap and zooplankton sampling stations during 1986.

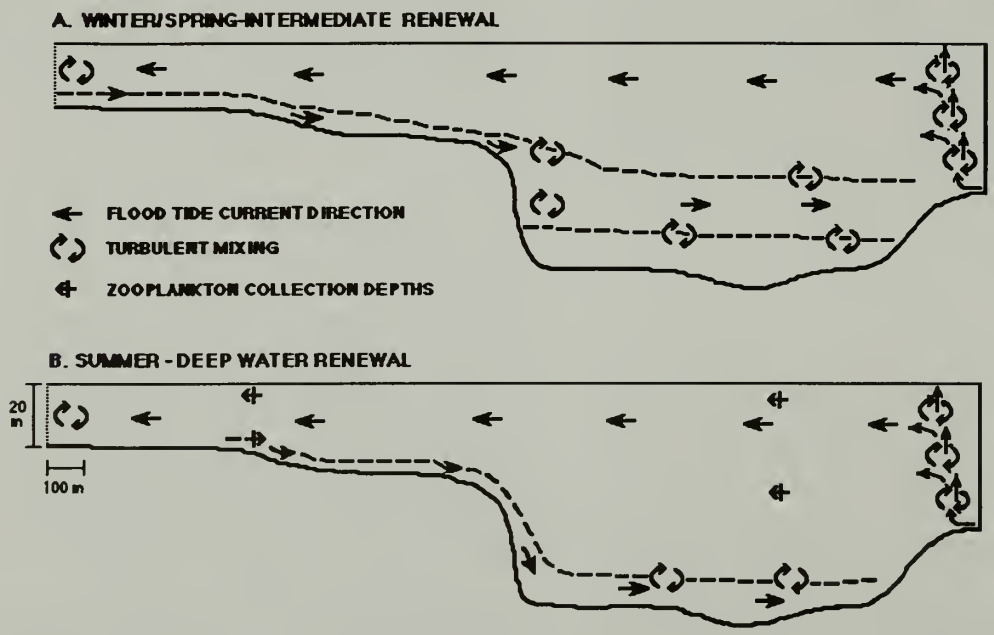

Fig. 2. Schematic diagram of flood tide circulation in McBride Inlet; two types of circulation occur, intermediate water renewal (A) during winter and spring and deep water renewal (B) during summer; modified from Cowan (1988).

Table 1. Mean density (±1 standard deviation) of benthic, epibenthic and pelagic organisms in McBride Inlet in 1984 (benthic sampling) and 1986 (sediment trap and zooplankton sampling).

	Benthic cores	Sediment traps	Zooplankton nets (no. m^{-3})		
	(no. 100-cm^{-2})	(no. per g cm^{-2} sediment)	surface	mid-depth	bottom
Benthic					
Nematoda	240.38±432.68	0.64±0.66			
Turbellaria	25.44±94.74				
Polychaeta	39.59±59.39				
Oligochaeta	0.88±1.53				
Bivalvia	76.36±111.21	24.44±34.88			
Epibenthic					
Harpacticoida	868.20±1603.48	8.43±2.08	0.01±0.02		4.00±5.66
Gammaridea		0.66±0.84			
Pelagic					
Copepoda-larvae	497.73±766.39	8.65±10.87	0.01±0.02		
Calanoida	343.60±452.48	18.97±10.29	74.26±127.87	2.9	330.38±449.18
Gammaridea	0.01±Å0.01				
Hyperiidea	1.41±5.66				
Euphausacea	0.57±0.01				
Cirrepidia-larvae	1.41±7.07	0.47±0.81			20.00±28.28
Chaetognatha					279±394.57
Total	2,169.08±2,624.38	72.77±52.37	74.27±127.86	2.9	340.37±463.30

organisms, such as nematodes, polychaete annelids and bivalve molluscs (probably the last pelagic-stage larvae of *Mytilus*), were secondary in numerical importance. Late stage copepodid and adult calanoid copepods, which are typically pelagic organisms, were also numerically important, averaging 3.4 ± 4.5 x $10^4/m^2$, including between ~ 7 and ~ 12 x $10^4/m^2$ at eight locations.

In comparison to the tidewater environs of McBride Inlet, which has restricted circulation and the submarine meltwater discharge, Riggs Glacier has open circulation to Muir Inlet and meltwater discharging over a delta; benthic and epibenthic fauna in front of Riggs Glacier were of comparatively low abundance.

A cursory examination of three representative core samples from McBride Inlet indicated very low diversity among the meiofaunal crustaceans (Table 2). Only two genera of harpacticoid copepods, *Halectinosoma* sp. and *Microarthridion littorale*, occurred. These taxa are typical of shallow subtidal,

Table 2. Range in composition (% numerical) of invertebrate taxa in benthic core, sediment trap, and zooplankton net samples from McBride Inlet, 1984 and 1986.

Taxa	Benthic core	Sediment trap	Zooplankton net
Copepoda			
Calanoida			
unidentified nauplii			
& copepodids	0.2	5-39	
Calanidae			
Calanus sp. copepodids			
Pseudocalanidae			
Pseudocalanus spp.	0-15	29-56	0-15
Pseudocalanus copepodids			83-91
Metriidae			
Metridia okhotensis		0-9	
Centropagidae			
Centropages abdominalis		0-2	
Acartiidae			
Acartia sp.	0-40		0-2
Acartia longiremis			0-1
Acartia sp. cf. *clausi*			0-1
Cyclopoida			
Oncaeidae			
Oncaea sp.		0-1	
Oithonidae			
Oithona similis		0-4	0-3
Harpacticoida			
Ectinosomatidae			
Halectinosoma sp.	15-100	7-29	
Microarthridion littorale	0-14	0-1	
Balanomorpha-cyprid larvae		0-5	
Amphipoda			
Gammaridea			
Cyphocaris challengevi		0-1	*
Hyperiidea-juvenile			
Euphausiacea			
Euphausiidae			
Thysanoessa raschii			*

*Incidental

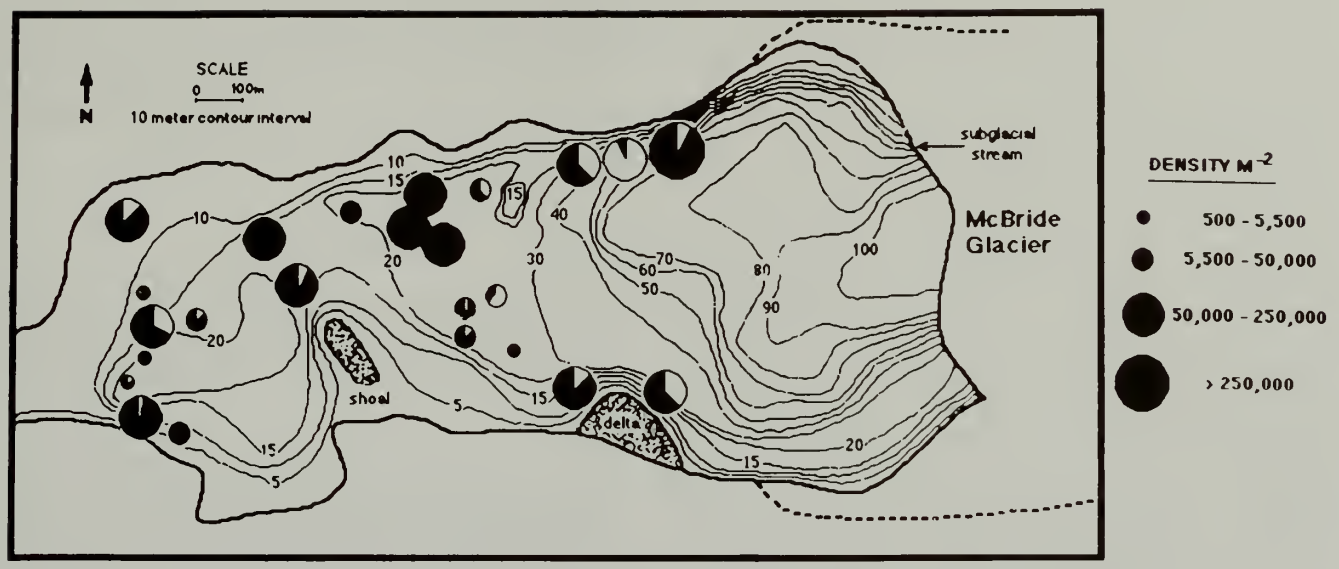

Fig. 3. Relative distribution and abundance of epibenthic and benthic (dark portion) and pelagic organisms (light portions) found in benthic core samples in McBride Inlet, 1984.

estuarine habitats, typically those dominated by medium to coarse sand substrates (Hicks and Coull 1983). Pelagic calanoid copepods were represented by two taxa, *Acartia* sp. and *Pseudocalanus* sp., both characteristic of coastal and estuarine communities. Of the naupliar and copepodid copepod stages, all nauplii appeared to be calanoids, and most of the copepodids were calanoids mixed with some unidentifiable cyclopoids.

Samples from sediment traps deployed in the deep basin in contact with McBride Glacier (Station #1, Fig. 1) and from the shallow "sill" area near the mouth of the Inlet (Station #4) verified that many benthic, epibenthic and pelagic organisms are associated with suspension settling from the turbid overflows and bottom currents (Table 1). Bivalves (*Mytilus* spp. larvae) and calanoid copepods were the most prominent taxa, where 24 and 19 organisms, respectively, were deposited per g/cm^2 of sediment in the traps; harpacticoids and copepod larvae (nauplii) were slightly less abundant, at 8 to 9 animals deposited per g/cm^2. Taxonomic composition of three representative sediment trap samples indicated that, similar to the benthic core samples, the harpacticoid *Halectinosoma* sp. and calanoid *Pseudocalanus* sp. were also the dominant taxa deposited in the traps (Table 2).

Near-bottom zooplankton net samples contained the most animals, ~300/m^3, which were predominantly calanoid copepods; harpacticoids and chaetognaths also occurred but were relatively uncommon, at 3 to 4 animals/m^3. In comparison, surface (overflow) samples averaged less than 1 organism/m^2, but one sample from station #1, close to the emergence of the meltwater stream, contained ~221 calanoids/m^3. Taxonomic composition (Table 2) of the zooplankton samples was indicative of pelagic marine (fjord) communities, dominated primarily by the pelagic calanoids *Pseudocalanus* spp. and, secondarily so, by other calanoids (e.g., *Calanus* sp., *Acartia* sp., *Centropages abdominalis)*, cyclopoids *(Metridia okhotensis)* and chaetognaths.

Discussion

Numerical and taxonomic distributions of benthic, epibenthic and pelagic organisms found in bottom or near-bottom sediments in McBride Inlet appear unrelated to either depth or distance from the meltwater plume arising from the subglacial stream (Fig. 1). Although benthic and epibenthic organisms generally dominated all samples, pelagic taxa appeared prominently in samples throughout the Inlet and dominated several samples taken from close proximity to the glacier face.

Zooplankton sampling in surface, intermediate and near-bottom waters illustrates that the source of animals in the suspended sediment probably is from Muir Inlet communities advected into McBride Inlet with the combined tidal and gravitational currents.

Prevalence of pelagic organisms in benthic samples infers mortality and sinking of the marine fauna from turbulent mixing at the rising meltwater plume. In fact, gravitational circulation induced by the freshwater outflow from the glacier and flood tidal currents are likely responsible for advection of marine waters and their associated fauna into the mixing region at the glacier terminus (Fig. 2). There, the least

euryhaline (salinity tolerant) fauna would suffer mortalities and are probably "stripped" from the water column and settle out with sediments across the Inlet. High densities of pelagic calanoids in the surface overflow at station #1 indicate pelagic fauna across a sharp gradient between this station and station #4, where the same organisms were comparatively rare. The benthic/epibenthic taxa (e.g., harpacticoids), on the other hand, may originate from the surface of bottom sediments within the Inlet, due to resuspension during strong near-bottom currents, probably in the vicinity of the sill (station #4), and are then transported into the deep ice-contact basin by bottom water flow. Interpretation of the bottom sediments closer to the glacier suggests that such resuspension is not prevalent in the deeper basin (Cowan 1988). This sill resuspension/mixing "model" may explain why benthic and epibenthic fauna, such as harpacticoid copepods, were rare in the benthic core samples collected in front of Riggs Glacier, which lacks the sill configuration.

Such a circulation pattern could also draw phytoplankton, nutrients, and detrital organic matter into McBride Inlet from Muir Inlet and thereby accrete these potential food resources to benthic and epibenthic communities. Although low in species richness, characteristic of highly perturbed or stable communities, the benthic-epibenthic assemblages appear to be exceptionally productive. In addition, the presence of all life history stages of the harpacticoids, including ovigerous females, suggests viable, endemic populations. Such persistence in the dynamic, turbid and locally turbulent, rapid sedimentation conditions, implies adaptive advantages for early colonization of ice-proximal, glacimarine environments.

Given the unique features of this modern environment, such an ice-proximal system (Powell, this volume; Cowan, this volume) provides a chronological window to the processes regulating benthic colonization of glacimarine sediments in basins that experience glaciation. Thus, the seeding process of the newly uncovered benthic environment in conjunction with glacial retreat may represent a general process which characterized benthic community development along the margin of the northeastern North Pacific Ocean during the last stages of Cordilleran glaciation. Both in regulating the source and rate of sediment flux to the bottom, and in driving circulation patterns in the fjord, patterns in glacial discharge may determine the composition and stability of the benthic community within its influence. Furthermore, primary and secondary production of this community may depend directly (carbon/nutrient sources) or indirectly (controlling circulation, turbidity and salinity) upon glacier discharge patterns. Certainly, in the case of the dynamic circulation processes we have investigated at McBride Inlet, the glacier-induced flows may actually account for transport and, through intense sedimentation, deposition of fjord pelagic organisms in the ice-proximal benthos. Our estimates, albeit imperfect, suggest that between 0.11 and 0.65 kg at Station 1 ($<$ 400 m from glacier terminus) and 0.01 kg at Station 2 ($<$ 640 m) of (wet weight) pelagic zooplankters may be deposited/m^2/annum in Muir Inlet. We speculate that this flux of organic matter is in part responsible for the high densities of benthic and epibenthic detritivores which we have found living there.

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Early Lake Ontogeny following Neoglacial Ice Recession at Glacier Bay, Alaska

by

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Abstract

This study explores the environmental forces controlling lake ontogeny at Glacier Bay as a model for early Holocene lake evolution in north temperate lakes worldwide. Long-term chemical and biological changes in lakes are investigated with two complementary research strategies: (1) limnological conditions are compared among 32 lakes of known age and in different stages of primary catchment succession and (2) sediment cores from these same lakes are analyzed stratigraphically for fossil diatoms to ascertain developmental trends in pH, alkalinity, algal composition, and trophic status at individual sites.

Trends in water chemistry inferred from the chronosequence approach include a progressive loss of alkalinity and dilution of surface waters, an increase in apparent color from organic acids, and a decline in pH. Because of considerable scatter in the chronosequence data, these changes are not apparent until several hundred years after deglaciation. Preliminary observations of biotic trends include an apparent succession of higher aquatic plants mediated by alkalinity changes and a rapid diversification of the diatom flora associated with a proliferation of new growth substrates, particularly macrophytes.

Several hypotheses concerning early postglacial land/water interactions are supported by these results, including (a) the progressive leaching of catchment soils makes lakes more dilute and acidic over time, (b) peat growth and regional paludification impede internal soil drainage and groundwater recharge, causing dilution and eventual dystrophication of surface waters, and (c) hydrologic and geologic differences among sites act to control the rates and direction of limnological change.

KEY WORDS: Paleolimnology, hydrology, lake chronosequence, succession, diatom stratigraphy, water chemistry, dystrophication.

Lake ontogeny, as an ordered progression of trophic states resulting from maturation of the landscape, has been viewed by some as a trend towards eutrophy and by others as an opposite trend towards oligotrophy. The more widely held view within ecology, that evolved lakes are more productive, is confounded by the process of cultural eutrophication. Nevertheless, many paleolimnological studies have noted biotic changes indicating an early postglacial increase in lake productivity (e.g., Davis et al. 1985). Likewise, stratigraphic evidence for progressive oliotrophication, in which lakes become more acid and unproductive over time, is equally strong (e.g., Whitehead et al. 1986). Such divergent results clearly suggest that lake ontogeny is a process in which trajectories and rates depend on initial geologic and climatic conditions as well as subsequent changes in vegetation, soils, and hydrology.

In order to explore more directly the environmental forces controlling lake development, we are presently studying a series of recently formed lakes along a deglaciation chronosequence in Glacier Bay National Park. We are investigating the early stages of lake ontogeny in relation to primary succession in vegetation and soils following more than 1,000 years of Neoglacial ice recession. This study emphasizes changes in water chemistry, primary production and phytoplankton composition, and the influence of catchment lithology and hydrology in regulating material inputs to lakes. We wish to test several hypotheses that have been generated by previous paleolimnological studies concerning these land and water interactions:

(1) There is a progressive decrease in the export of dissolved solids from catchment to lake waters associated with the leaching of soluble minerals from upper soil horizons. Lakes eventually become more acidic over time.

(2) Increased nutrient inputs, particularly N and P, associated with early pedogenesis may cause an initial increase in primary production and a shift from benthic

to planktonic algal forms. This productivity increase may be short-lived as the pool of 3 primary mineral phosphorus is subsequently depleted in the upper solum.

(3) Hydrologic and lithologic differences among sites act to control initial water chemistry and the rate of limnological change associated with terrestrial primary succession.

(4) In environments with high net precipitation, the development of histic (peaty) soils impedes internal soil drainage and leads to the increased export of humic materials and the widespread dystrophication of surface waters.

Our focus on the early phases of lake development provides an important analogue to events that occurred on a continental scale thousands of years ago. The period shortly following continental deglaciation was one of dynamic environmental change associated with climatic warning and the re-invasion of plants and animals. All paleolimnological evidence thus far points to an equally rapid transformation of aquatic environments associated with terrestrial change.

The problem of early lake ontogeny has been attacked with two independent and complementary research strategies: (1) limnological conditions are being compared among 32 lakes of known age and in different stages of primary catchment succession and (2) sediment cores from a selection of these same lakes are being analyzed stratigraphically for fossil diatoms and algal pigments to ascertain developmental trends in pH, alkalinity, and algal compositions at individual sites. In the chronosequence approach, limnological change is inferred from the comparison of younger and older sites, presupposing that the primary difference among lakes is age since formation. Of course, lakes may differ in other important respects, such as the geological and hydrologic setting, which might add considerable variation to any chronological pattern. If one takes into account such watershed differences, however, the divergence of certain lakes from an otherwise dominant trend should be instructive.

The paleolimnological approach, on the other hand, eliminates the uncertainty of inter-lake comparison by following the historical development of a single site, but it does so at the expense of direct limnological observation. Difficulties arise because temporal resolution from sediment stratigraphy is often poor, modern analogues are often lacking for early postglacial environments, and reliable calibrations of sedimentary components required for quantitative reconstructions exist for only a few parameters, such as pH. Despite such limitations, paleolimnology can serve to verify processes inferred from a representative series of lakes taken at a single point in time. A combination of comparative limnology and core work as undertaken here is thus synergistic in that it complements the fine resolution of direct observation with the certainty of stratigraphic change.

Study Sites

The 32 lakes in this study are situated at low elevation ($<$200m) in small primary catchments receiving no drainage from other lakes or major streams; most are small (3-16 ha) and moderately deep (Z_{max}=3-18 m). More than half are located within Glacier Bay proper and as such are no older than the Bartlett Cove moraine (ca. 200 years). Eleven of the youngest lakes, found along Muir and Wachusett Inlets, have catchments in early stages of terrestrial succession. Another seven sites are situated in the spruce/hemlock forests of the lower bay, while three lakes are in transitional areas at mid-bay. Eleven additional lakes, which extend the chronosequence to older surfaces, are located near Lituya Bay (350-400 years), Taylor Bay (1,200-2,000 years), the terminus of the LaPerouse and Dagelet Glaciers (ca. 2,000 years), and on Pleasant Island (14,000 years). The vegetation surrounding these lakes ranges from hemlock/spruce forest at Lituya Bay to an increasing prevalence of muskeg in the older catchments.

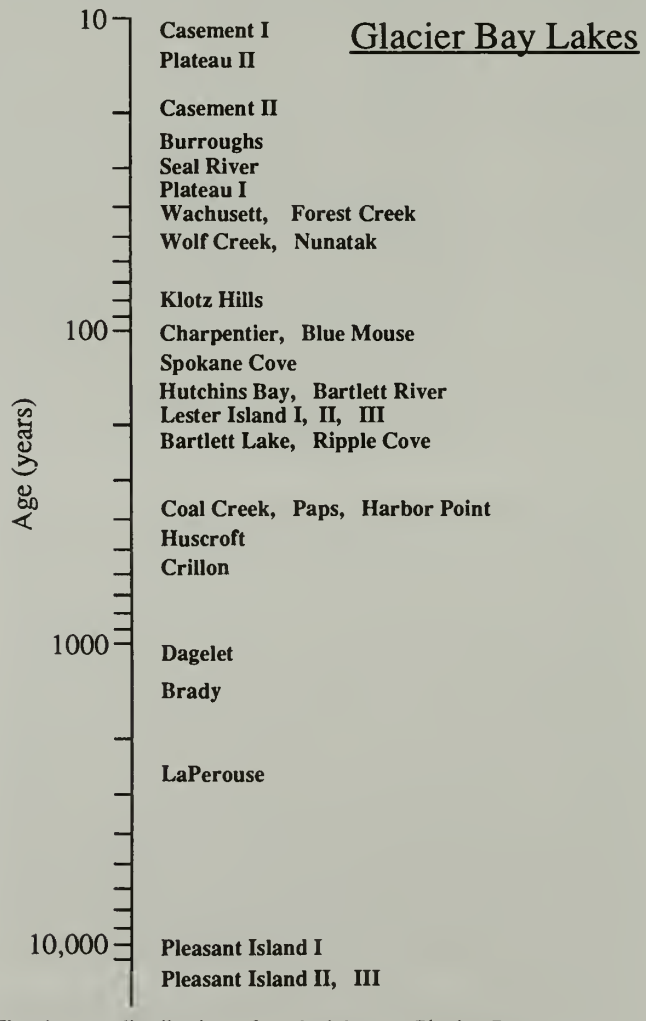

Fig. 1. Age distribution of study lakes at Glacier Bay.

The exact age of the early Neoglacial sites is subject to verification by radiocarbon dating (presently in progress). The late Wisconsinan deglaciation of Pleasant Island is already known from ^{14}C dating at one of our sites. The age distribution of the study lakes is shown in Figure 1.

Methods

In the course of this study, all lakes will have been sampled at least three times (July 1987, Sept. 1988--already completed, and May 1989) to assess seasonal and year-to-year variability in limnological conditions; these results are supplemented for many of the sites by preliminary data from September 1983, 1984, and June-July 1986. At each visit, a temperature profile of the lake is recorded, epilimnetic and hypolimnetic water samples are taken, and collections of zooplankton, phytoplankton, and attached algae are made. Laboratory analyses of field collections include major cations and anions, nutrients (total-P, total-N, and dissolved-Si), apparent color, conductivity, chlorophyll, and dissolved organic carbon (DOC). In addition, we have surveyed the composition and abundance of macrophytes in each lake, mapped basin morphometry by recording depth meter, and collected unweathered till samples from soil pits in each catchment to assess basin lithology. We have also cored the sediments of all 32 lakes with a piston corer operated by rigid drive rods from the lake surface. Hydrological work associated with this project is described by J. Almendinger in this volume.

Results

Chronosequence

A summary of epilimnetic water chemistry from July 1987 (Fig. 2) shows a wide range of ion concentrations for lakes in Glacier Bay National Park (0.1-5 meq/L). The more concentrated lakes with ion sums >1 meq/L are dominated by Ca^{+2} and HCO_3^- ions, whereas the more dilute lakes have a mixed ionic composition with Na^+ and Cl^- in greater proportion. This pattern results from the predominance of dilute lakes along the outer coast where seaspray is an important component of precipitation. Earlier results from 12 of these sites sampled in 1983, 17 sampled in 1984, and 8 sampled in 1986 are very similar. Chlorophyll-a concentrations for these same sampling periods are generally below 2 or 3 μg/L, and total phosphorus is less than 10 ppm, implying highly oligotrophic conditions in most lakes.

Although the data are as yet incomplete, a number of limnological parameters exhibit striking trends with lake age

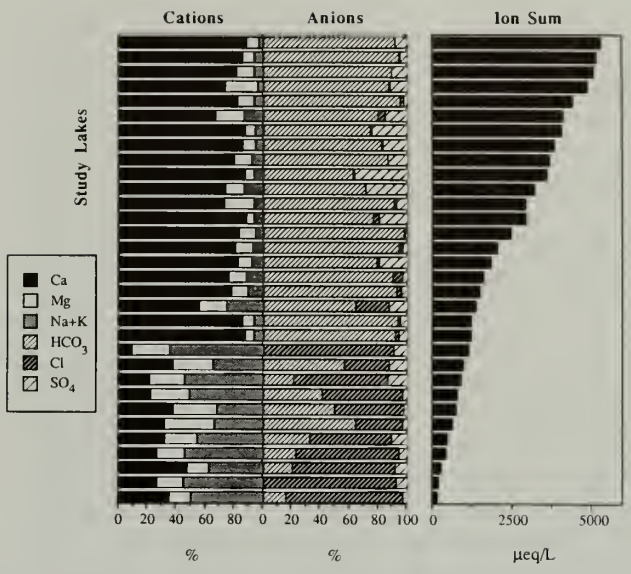

Fig. 2. Major ion chemistry of epilimnetic water samples taken in July 1987; cations and anions expressed as percentages of their respective sums in μg/L; ion sum = cations + anions.

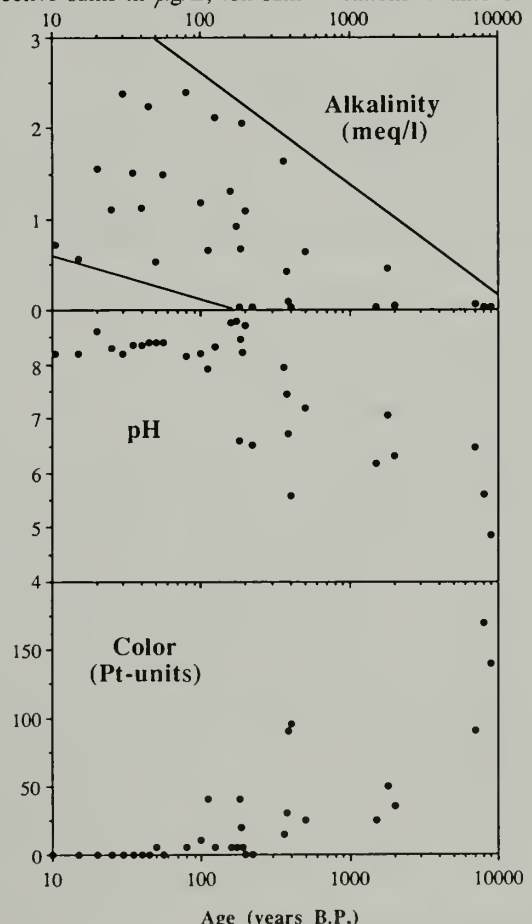

Fig. 3. Relationship between surface age and epilimnetic alkalinity, pH, and apparent color for 32 lakes sampled in July 1987.

that suggest the processes hypothesized previously for early lake ontogeny. All major cations and all anions except Cl^- show declining values along the chronosequence of sites from youngest to oldest. The general trend is illustrated here (Fig. 3) by data for alkalinity (primarily HCO_3^-). While there is a good deal of scatter in the data for any particular time slice, there are clearly no "old" lakes with high alkalinity, and conversely no "young" lakes with low alkalinity. Other solutes show more or less variance in this pattern, while certain sites are consistent outliers for all ions. Notable trends are also evident in pH and apparent color, a relative measure of organic acid content (Fig. 3). Epilimnetic pH is uniformly high (>8.0) for lakes less than 200 years old but shows a declining pattern with lake age among older sites, beginning with two lakes in the Bartlett Cove area. This pH trend reflects the greater carbonate buffering of the younger lakes (high alkalinities) and the increasing concentration of organic acids (as illustrated by apparent color) in the older lakes.

The scatter in the above trends illustrates the individualistic nature of lakes and underscores the difficulty in using chronosequence to infer universal patterns in lake ontogeny. In some cases, the variability among lakes of similar age can be ascribed to differences in geologic setting, where certain rock types contribute a greater flux of solutes to a lake than do others. For example, three lakes along the lower reaches of Wachusett Inlet exhibit SO_4^{-2} concentrations of 30-40 ppm, an order of magnitude higher than the mean for all other lakes in the data set (3.1 ± 4.2 ppm, ± 1σ). This sulfate "anomaly" probably results from weathering of locally abundant sulfate or sulfide minerals in the watersheds of these lakes.

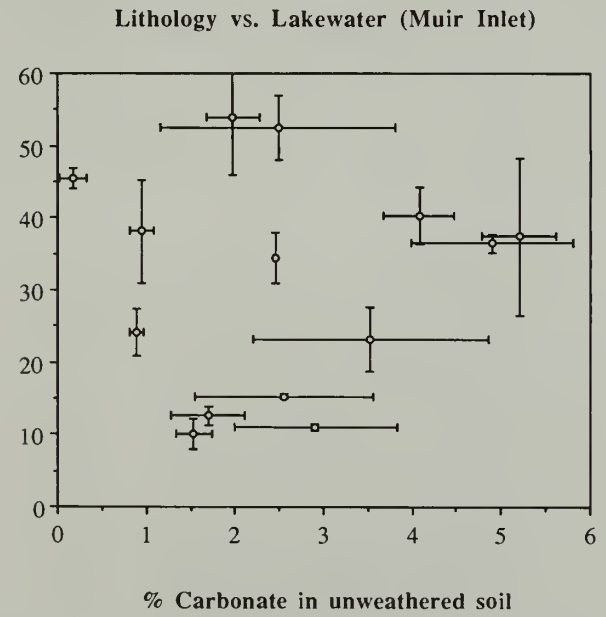

Fig. 4. Relationship between the carbonate content of unweathered soil samples and epilimnetic Ca^{+2} concentrations at study sites in the Muir Inlet area; error bars = ± 1σ, representing 2-3 soil pits and 2-4 water samples (from consecutive years).

In most cases, however, catchment lithology explains little of the variance in lake chemistry, as shown by a comparison of soil and water chemistry for sites in the Muir Inlet area (Fig. 4). Among this subset of our youngest lakes (all less than 80 years old), there is no discernible relationship between the carbonate content of unweathered soil samples and lakewater Ca^{+2}. Such variability among lakes of similar age can be ascribed instead to differences in hydrologic setting and the relative contributions of groundwater, surface flow, and direct precipitation to the lacustrine water budget. Groundwater (including stream flow) typically carries a much higher load of dissolved solids than does runoff or precipitation, so that lakes receiving groundwater inputs are more concentrated than lakes that do not.

With respect to our biological parameters, the data are as yet too preliminary to confirm patterns of trophic development. Among nutrients, total-nitrogen appears to increase during the earliest stages of lake development, reflecting perhaps the expansion of N-fixing alder in the terrestrial vegetation during the first few decades following deglaciation. This trend may be manifest in an increase in phytoplankton production during the first two centuries of the chronosequence.

This year's macrophyte survey points to a very striking relationship between lake alkalinity and the abundance of a number of higher aquatic plants, such as *Nuphar, Hippuris, Menyanthes,* and several species of *Potamogeton*. This relationship is probably due to the ability of different species to photosynthetically fix CO_2 or HCO_3^- from lakewater and is significant in lake ontogeny because of the loss of alkalinity with landscape maturation. Because macrophytes provide growth surfaces for other organisms and contribute heterogeneity to aquatic habitats, a macrophyte succession mediated by alkalinity changes has major implications for the biotic evolution of lakes in Glacier Bay.

Paleolimnology

The stratigraphy of diatoms in lake sediment cores can be used to reconstruct changes in water chemisty, as well as the availability of substrates such as macrophytes for algal growth. Fig. 5 shows the diatom stratigraphy of Lester #2, a 180-year-old moderately alkaline lake on Lester Island. The basal sediments are highly inorganic and contain a restricted diatom flora of three benthic taxa common in alkaline lakes. The dominance in these basal sediments of *Gyrosigma spencerii*, a large, heavily silicified taxon found in high-energy environments, probably reflects high turbidity resulting from unstable slopes in the newly deglaciated landscape. This

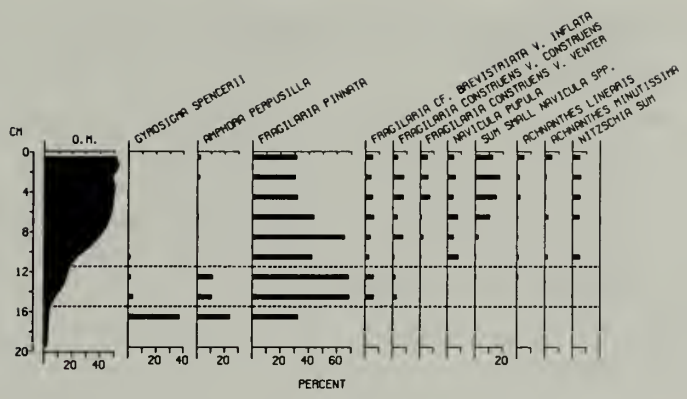

Fig. 5. Preliminary diatom analysis of a core from a 180-year-old lake on Lester Island; O.M. = % organic matter in dry sediment from loss-on-ignition.

species declines in abundance as the organic content of the sediment increases, a result of plant invasion and stabilization of the surrounding catchment. Subsequently, both benthic and epiphytic taxa characteristic of cicumneutral and alkaline waters invade and expand, including several *Fragilaria* and *Achnanthes* spp., *Navicula pupula, N. tantula, N. minima, N. seminulum, N. subatomides,* and *N. subrotundata.* This diversification of the flora undoubtedly reflects the proliferation of new habitats for diatom growth, particularly the invasion and expansion of macrophytes, such as *Potamogeton* spp. and *Equisetum.* Ultimately, we plan to use recently collected samples of modern diatom communities in Glacier Bay lakes as analogues in the interpretation of the core samples, permitting quantitative reconstruction of changes in water chemistry through time, especially trends in pH, alkalinity, and water color.

Discussion

The preliminary trends observed in this study allow us to speculate on properties of the land/water system that might cause limnological change over the long course of time. The impacts of vegetational succession, soil development, and hydrological change, all potential agents of lake ontogeny, cannot be observed directly because of the slow pace at which they proceed. However, their influence can be inferred by correlation of apparent trends in terrestrial and aquatic succession.

In the case of soil development, we have a fairly clear picture of carbonate loss, pH decline, and nitrogen increase during the first century of terrestrial succession in Glacier Bay (Crocker and Major 1955). Thus, the weathering of soluble minerals from upper soil horizons may be practically responsible for lakes becoming more dilute and acidic over time. Likewise, the steady accretion of an organic soil horizon no doubt contributes to a greater flux of organic acids that stain the waters of older lakes (Engstrom 1987). However, it is as yet unclear whether lake alkalinities actually decline over the same period of time (0-200 years) that initial soil development is thought to occur. Furthermore, while surficial catchment drainage may lose ionic strength because of weathering, groundwater at depth should be relatively unaffected by this process. Thus, lakes receiving even a moderate load of dissolved solids from subsurface flow should be slow to respond to terrestrial succession.

That essentially all of the older sites along the outer coast and on Pleasant Island (most in carbonate-rich terrain) are dilute and at least somewhat acidic implies that eventually groundwater inputs to lakes decrease over time, either in volume or in concentration. A decrease in groundwater flux could be caused by a long-term decline in recharge associated with soil development. Indurated soil horizons and thick accumulations of peat, which begin forming several hundred years after disturbance in Southeast Alaska (Ugolini and Mann 1979), could gradually inhibit internal soil drainage and transform groundwater recharge into surficial flow. Catchment drainage coursing through peat or weathered soil horizons would bear a much smaller load of dissolved solids than the groundwater it displaced, and lakes receiving these inputs would gradually become more dilute and acidic (Almendinger, this volume).

From this model on lake ontogeny, we could expect that individual lakes would follow different trajectories, depending on hydrologic and geologic settings. Lake basins in granitic terrain, for example, would likely begin with more dilute waters than basins in sedimentary rock and might become acidic more rapidly. On the other hand, groundwater inputs should buffer lakes from the immediate effects of soil development so the basins receiving groundwater discharge should change more slowly than lakes fed solely by surficial drainage and direct precipitation. In general, however, lake evolution in Glacier Bay can be viewed as a convergent process of progressive dilution and acidification.

At present, such trends can only be inferred for low elevation sites in Glacier Bay where organic-rich soils develop under coniferous vegetation. The cool, moist climate of Alaska's temperate rainforests offers an ideal setting for the edaphic changes embodied in this model of lake ontogeny. However, similar conditions exist throughout the boreal forest regions of North America and Europe, and the patterns of limnological change envisioned for Glacier Bay may thus apply to many of the lakes created by continental glaciation.

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Hydrologic Control of Lake Chemistry on Lester Island, Glacier Bay National Park

by

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Abstract

Three lakes on Lester Island in Glacier Bay National Park, Alaska, are all of the same age yet have significantly different chemistries, ranging from extremely dilute to fairly alkaline. Weirs were used to measure streamflow into each lake, and a "mini-piezometer" was used to measure the groundwater gradients through each lake bed. The results indicate that the alkalinity of a lake is proportional to both the inlet streamflow and the amount of shoreline along which the lake receives groundwater. Changes in the chemistry and quantity of the components of a lake's water budget, particularly the alkaline stream and groundwater components, determine the changes in the chemistry of the lake. Several possible mechanisms by which the stream and groundwater components can naturally decrease, causing a trend of decreasing lake alkalinity over time, are discussed.

KEY WORDS: Paleoecology, lake hydrology, groundwater, streamflow, lake ontogeny.

Paleoecologists view lakes and their sediments as devices that record the environmental history of their catchments. Typically, the sediment record is used to infer the climatic history of the catchment. However, even in the absence of climatic change, other factors can also cause a change in the sediment record. For example, landscape development (soil and peat formation combined with vegetational succession) can cause changes in the chemical and biological character of a lake and hence also its sediments. Understanding the relationships between landscape development, lake chemistry, and the sediment record is valuable not only for clarifying our climatic interpretations of lake sediments but also for characterizing natural, as opposed to anthropogenic, changes in lakes and their catchments.

It might be expected that nearby lakes of similar size lying in the same general substrate of the same age (i.e., with the same amount of landscape development) would have similar chemistries. However, three small lakes located on Lester Island have quite different chemical compositions despite essentially identical age, substrate, and climate. All three lakes are buffered by the carbonate system but to different degrees. Lake One is extremely dilute with an epilimnetic alkalinity of about 0.04 meq/L, while that of Lake Three is over fifty times higher at 2.3 meq/L; Lake Two has an intermediate value of 0.65 meq/L.

Differences among the three lakes in their water sources may account for their different chemistries. All the lakes receive direct precipitation and probably also some overland flow and interflow from the upper soil horizons directly beneath the organic duff. However, neither precipitation nor shallow runoff contains significant amounts of alkalinity (the upper 50 cm or so of the inorganic soils on Lester Island are leached of carbonate). Thus, the source of the alkalinity must be deeper groundwater flow, which either seeps directly into the lakes or enters them via streamflow. Changes in the chemistries of the lakes can nearly always be proximally ascribed to changes in their hydrologies, whether or not the hydrologic changes are ultimately caused by climatic shifts or landscape development, or both.

Methods and Results

All three lakes have surficial outlets, although those for Lakes One and Two do not necessarily flow during the drier summer months. However, only Lake Three is fed by a stream

that appears perennial; Lake Two is fed by a stream that dwindles to negligible flow by mid- to late summer, and Lake One has no inlet stream. The waters carried by these inlet streams are fairly alkaline, averaging about 3.5 meq/L. To quantify the flow rates, we placed V-notched weirs at each inlet (and outlet), and the results in this paper refer to spot measurements taken at the weirs in late July 1988. With these measurements, I calculated the inlet flow at Lake Three to be 1.4 L/s, 35 times greater than the 0.04 L/s flow of the inlet at Lake Two. Clearly the most alkaline lake (Three) is receiving the most input from alkalinity-rich streamflow, while the most dilute lake (One) receives no streamflow at all; Lake Two has an intermediate alkalinity and an intermediate inlet streamflow.

Carbonate-rich water may directly enter the lake via groundwater seepage. The direction of this seepage, into or out of the lake, may be checked by comparing the hydraulic head of the lake (i.e., the lake level) with the head of the groundwater at a point somewhat below the lake bottom; e.g., 50 cm or so into the sediments. A "mini-piezometer" is merely a pipe screened at its tip and driven a convenient depth into the lake sediments. If the water level in the mini-piezometer is greater than lake level, then groundwater is seeping into the lake; if lake level is greater than the mini-piezometer water level, then water is seeping out of the lake through its bottom. The mini-piezometer we used, as designed by Winter et al. (1988), has a manometer arrangement to facilitate comparing the water levels of the lake and mini-piezometer.

For geometric reasons, most groundwater flow in and out of lakes tends to occur near the shoreline (McBride and Pfannkuch 1975). Hence, a mini-peizometer survey around the lake margin should characterize the predominant pattern of lake-groundwater seepage. During May and June 1988, we found no groundwater seepage into the dilute Lake One, and Lake Two had only a small segment of its shoreline (about 100 m, or less than 8% of the total shoreline) with groundwater in-seepage. The relatively alkaline Lake Three had by far the most shoreline receiving groundwater seepage, 350 m or about 45% of the total shoreline (Fig. 1). These results are only qualitative, and to convert them to quantitative, groundwater flow rates would require the knowledge of the actual head gradients through the lake bottom and its permeability. Nonetheless, these results are consistent with the hypothesis that groundwater inflow is greatest for Lake Three, less for Lake two, and essentially nonexistent for Lake One.

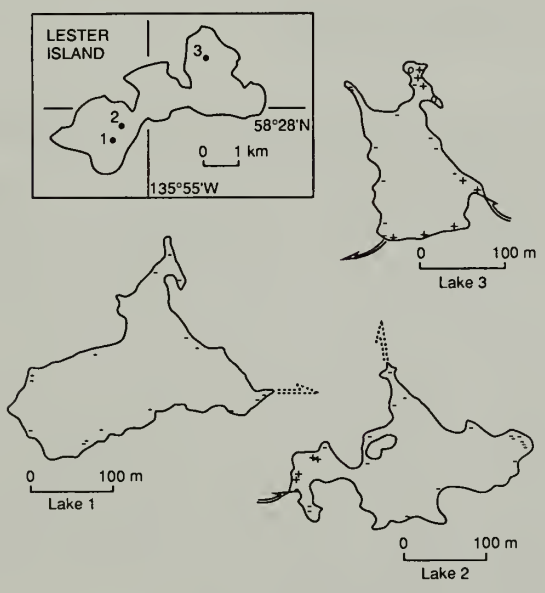

Fig. 1. Qualitative mini-piezometer readings of groundwater seepage for the three Lester Island lakes: "+" = groundwater seepage into the lake; "−" = seepage out of the lake; "0" = no seepage. Lake Three has the most shoreline with groundwater inseepage, followed by Lake Two; Lake One has no groundwater input. Inlets and outlets are shown by either solid (perennial) or dotted (ephemeral) arrows.

Discussion

Short-term Scenario

Ultimately, the chemistry of a lake is determined not by its inputs alone, but by a dynamic balance between inputs and outputs, each with a characteristic flux and chemistry. Moreover, a few point measurements of an input (e.g., the chemistry and flow of an inlet stream) may not be representative of what the lake receives over the course of an entire year or several years. Thus, we have placed water-level recorders in each lake to monitor daily (or shorter) changes in (1) inlet and outlet streamflow and (2) groundwater seepage (estimated by a few recording piezometers pounded through each lake bottom) over the course of the next year. A small weather station on a platform near the middle of Lake Two will be used to estimate evaporation rates. Daily precipitation amounts for the coming year should be obtainable from the U.S. National Park Service headquarters in Bartlett Cove, which is within a few miles of our lake sites on Lester Island. The principal unknown quantity in our lake water budget is the input from shallow surface runoff and interflow; as a first approximation, we will calculate this shallow flow by difference.

Long-term Scenario

As demonstrated in this paper, knowledge of the hydrology of lakes is necessary to understand more fully their chemistries over the short term. The larger question is, What insight can this hydrologic knowledge give concerning long-term changes and trends in lake chemistry? Or, How does lake hydrology affect lake ontogeny? From our survey of lakes in and around Glacier Bay, the general trend seems to be that lake alkalinity decreases over time, as the landscape changes from the exposed, unweathered substrate of recently deglaciated regions to a peat-covered acid landscape, given the proper conditions. While it is by no means clear that all lakes and landscapes follow this pattern, there are some hydrologic reasons why lakes in the Glacier Bay region might be expected to lose alkalinity over time. These are as follows:

(1) The upper soil becomes leached of its carbonate content. While this process certainly occurs, it should have a major effect only on lakes whose primary source of alkalinity has been from overland flow or shallow interflow. Moreover, this mechanism should operate for only the first few hundred years of lake ontogeny, if conditions on Lester Island can be considered representative. The lack of alkalinity in tea-colored surface ponds on Lester Island is evidence that the leaching of roughly the upper 50 cm of soil has already been sufficient to remove the alkalinity from the shallow surface runoff collected by these ponds.

Can this surface leaching be extrapolated to the deeper aquifer? If the rate of leaching on Lester Island is maintained, then 2.5 m of substrate could be washed of carbonates each millenium, and it is conceivable that a relatively shallow aquifer could eventually become completely leached of its carbonates. However, we have no evidence of such extreme circumstances, and it seems more conservative to assume that if a lake receives deeper groundwater flow then that lake will maintain some measure of alkalinity.

(2) The hydrologic character of the catchment surface may shift in such a way that groundwater recharge is reduced, causing the water table to lower. And, in general, a lower water table causes less groundwater flow into streams and lakes (because hydraulic head gradients are less steep). Several mechanisms could cause such a decrease in groundwater recharge. First, early in the history of a lake, evapotranspiration from the catchment surface would tend to increase as the vegetation of the site shifted from open landscape to a spruce-hemlock forest. That is, increased evapotranspiration takes a larger portion of the rainfall, leaving less water available to recharge the water table. Presumably, once a full canopy of conifers occupied the catchment, the evapotranspiration would remain high without further increase. Incidentally, the loss of spruce to the ongoing bark-beetle infestation on Lester Island should reduce evapotranspiration, at least over portions of the island, theoretically allowing a rise in the water table.

The surface of the catchment may also change in such a way that increases shallow runoff (either overland flow or interflow), at the expense of groundwater recharge. One proposed mechanism for such a surface change is the formation of an iron-cemented hardpan in the upper soil (Ugolini and Mann 1979), causing increased lateral flow and decreased infiltration of water. This type of hydrologic change could reduce lake alkalinity by both increasing the input of dilute runoff and decreasing the input of alkaline groundwater.

(3) Isostatic rebound could raise the landscape, including lake basins and stream channels, relative to the water table. For a given substrate, the elevation of the water table relative to sea level is dependent on the amount of recharge and on the hydraulic gradient (slope of the water table, essentially) necessary to move that groundwater down and away for discharge to the ocean. If recharge does not change, then the elevation of the water table relative to sea level should remain approximately constant, even as isostatic rebound pushes the land up through the more or less stationary surface of the water table. As discussed above, a lower water table relative to the land surface translates into reduced groundwater input to lakes and streams.

Summary

The epilimnetic alkalinity of a lake is proportional to the influx of alkaline-rich streamflow and groundwater. Over time, lake alkalinity may decrease because of a decrease in the alkalinity of the inflowing waters (caused by carbonate leaching of the soil) and because of a decrease in the rate of inflow of alkaline-rich water (caused by a lowering of the water table).

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The Importance of Glacier Bay to Tests of Current Theories of Plant Succession

by

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Abstract

Early research at Glacier Bay contributed substantially to the development of the concept of facilitation; i.e., that early successional dominants ameliorate the environment, making it more favorable for later successional species and less favorable for themselves. In the last fifteen years, detailed study of secondary succession has lead ecologists to conclude that competition may generally be a more important successional process than facilitation. Glacier Bay is the most frequently cited example of an environment where facilitation is probably a major process. Glacier Bay is thus an ideal site to study the mechanisms by which early successional species affect growth of later species, because it is likely that some of the effects of colonizers upon later successional species are positive (facilitative) and others negative (competitive). Species interact in a variety of ways, including competition for light and nutrients and alteration of the physical structure and chemistry of soil. The physiological basis for competition and facilitation depends on the light and nutrient requirements of component species and on the order in which species arrive at uncolonized sites. There are consistent correlations among these physiological and life-history traits which provide a basis for predicting the nature of interactions among species and the probability that competition or facilitation may occur in a particular successional sequence.

KEY WORDS: Competition, facilitation, Glacier Bay, growth, nitrogen, succession.

Plant succession, the directional change in vegetation through time, is a common phenomenon in most ecosystems. The first comprehensive explanation for this phenomenon (Clements 1916) was that those species which dominate in early succession alter their environment so that it becomes more favorable for the establishment and growth of later successional dominants and less favorable for themselves. This concept, frequently termed facilitation, is presented in many introductory ecology texts (e.g., Odum 1971; Ricklefs 1973) as the major mechanism causing successional change. The concept was developed largely on the basis of the correlation between changes in environment and changes in species composition.

In recent years, there have been a large number of experimental studies that have looked for evidence of facilitation, frequently by removing early successional species to see whether this retarded or prevented successional change. In many cases, removal of early successional species stimulated or had no effect on growth of late successional species, suggesting that the major impact of early successional species was neutral or competitive rather than facilitative (e.g., Keever 1950; Niering and Goodwin 1974; Parrish and Bazzaz 1982;

Hils and Vankat 1982; Tilman 1985). These conclusions were summarized in literature reviews by Drury and Nisbet (1973) and Connell and Slatyer (1977). Connell and Slatyer (1977) suggested that there are basically three ways in which early successional dominants might affect those species which dominate later in succession. The net effect of early successional species may be stimulatory (facilitation), inhibitory (competition) or negligible (tolerance). In their review of the literature, they concluded that all experimental evidence pointed to changes in competitive balance as the major cause of successional change. They could find no evidence of facilitation in those experimental studies which they reviewed. Unfortunately, virtually all of these studies involved secondary successional sequences, a situation where soils are already well developed, and one might expect competitive interactions to be most important. In primary succession, where soils have not previously supported plant growth, and in severe environments where there are fewer soil resources available, there would seem to be greater possibility that early successional species might ameliorate the environment, thus facilitating growth and establishment of late successional species (Connell and Slatyer 1977). For example, the facilitative effects of leguminous nitrogen-fixers have been demonstrated in reclamation of severely disturbed habitats such as mine tailings (Palaniappan et al. 1979; Finegan 1984).

Discussion

Glacier Bay is probably the best studied primary successional sequence in the world. Previous work supports the idea that facilitation is an important mechanism of successional change in this ecosystem. The first evidence for this idea came from the work of W.S. Cooper (1923, 1931), who described the pattern of successional change in vegetation. He showed that the change from domination by alder (*Alnus sinuata*) and/or willow (*Salix alaxensis*) to domination by Sitka spruce (*Picea sitchensis*) was correlated with an increase in air temperature and with increased thickness of the humus layer developed by the shrubs. He made no attempt to evaluate the relative importance of change in environment due to glacial recession (change in temperature) vs. change in vegetation (humus development). He simply described the change in vegetation that was correlated with the change in these parameters. He was apparently unaware of the nitrogen-fixation potential of alder in that he never mentioned nitrogen as a factor contributing to successional change. It is also noteworthy that Cooper (1923) commented that willow seemed to be important in many situations in promoting establishment of spruce, apparently because it provided the humus that was necessary for successful spruce establishment but without producing an extremely dense canopy such as that characterized by alder. Cooper noted that alder generally preceded spruce as an important successional stage, but that willow thickets could lead to spruce forests without an intermediate alder stage. In fact, Cooper noted that in many alder thickets there were very few spruce seedlings, leading to the open question of how these alder thickets might eventually succeed to spruce. We feel that these questions raised by Cooper remain largely unresolved.

A second source of evidence for facilitation at Glacier Bay comes from the studies of Crocker and Major (1955), who demonstrated a correlation between nitrogen accumulation and community development. They suggested that nitrogen accumulation due to symbiotic nitrogen fixation by alder was responsible for the nitrogen supply that supported the development of vegetation through succession.

The only direct evidence for facilitation at Glacier Bay comes from the work of Lawrence and colleagues who found that both *Dryas drummondii* and alder stimulated growth in cottonwood (*Populus trichocarpa*) in early succession (Lawrence 1951; Schoenike 1958; Lawrence et al. 1967). There is presently no information on whether the presence of alder affects growth of spruce, the final successional dominant. We wish to emphasize that, although Glacier Bay is considered the best documented case of facilitation, much of this evidence is correlational, and no clear effect has been established of alder upon the growth of spruce, the final successional dominant. We suggest that further experimentation, similar to that performed by Lawrence with cottonwood (op. cit.), should be carried out with spruce. We are currently conducting such experiments.

In interior Alaskan floodplains, there is a successional sequence similar to that which occurs at Glacier Bay. Following deposition of open silt bars by river flood events, these silt bars are colonized by willows and poplars, which grow relatively slowly (Viereck 1970). Subsequently, alders establish, and over the next two decades alders are responsible for about half of the nitrogen fixation which occurs during the entire successional trajectory (Van Cleve et al. 1971). The sequence of species (alder, poplar, spruce) and the role of alder in causing nitrogen accumulation through succession appear quite similar to the situation at Glacier Bay. However, experimental studies on the Alaskan floodplain demonstrated that the competitive effects of alder upon spruce were greater than the facilitative effects (Walker and Chapin 1986). This raises questions about the role of facilitation in primary succession and suggests that the relative importance of competition and facilitation deserve more thorough study in primary succession.

The study in the Alaskan floodplain raised even more basic questions about mechanisms of successional change. It

Table 1. Major processes causing successional change.

1.	**Stochastic events**
	Disturbance
	Seed rain
2.	**Life history processes**
	Arrival
	Germination
	Maximum potential growth rate
	Longevity
3.	**Facilitation**
	Soil stabilization
	Nitrogen fixation
	Improved soil water regime
4.	**Competitive inhibition**
	Inhibition of germination
	Shading
	Root competition
	Cover for herbivores
	Allelopathy
5.	**Herbivory**

appeared that alder had multiple effects on spruce, some of which were facilitative (nitrogen accumulation and possible reduction of water stress due to shading) and others of which were inhibitory (inhibition of germination by litter and forest floor development and competitive inhibition of growth due to both shading and root competition, Walker and Chapin 1986). We suggest that it may be more constructive to examine the specific mechanisms by which alder affects spruce than to worry about whether succession occurs by competition or facilitation (Walker and Chapin 1987). Undoubtedly, the processes of competition and facilitation are a consequence of numerous types of species interactions (Table 1).

In summary, the literature suggests that in secondary succession, life history patterns and competitive interactions are clearly responsible for most successional changes in vegetation. However, in primary succession, many processes may be important in causing successional change, some of which are facilitative in nature and some of which are inhibitory. Perhaps in the Alaskan floodplain, the lack of evidence for facilitation was a consequence of a substantial pool of soil nitrogen initially present in the soil (Walker 1989). The best test for facilitation (perhaps interacting with competitive processes) would be in a situation where initial soil nitrogen pools are minimal, as at Glacier Bay (Crocker and Major 1955).

There are several additional traits which make Glacier Bay a unique situation for successional study. Glacier Bay is the site of one of the most rapid glacial retreats in recorded history. Thus, the various stages of succession are spread along an 80 km transect, gradually intergrading from areas that are just being released from ice to mature 250-year spruce-hemlock forest. Because the environment at Glacier Bay is favorable for tree growth, the vegetation in any one site changes rapidly, so that significant successional change occurs within the professional lifetime of a single investigator.

Secondly, the historical record at Glacier Bay is excellent in terms of careful documentation of the dates when various points on the landscape became ice-free and the types of vegetation which occupied these sites at known times in the past. Consequently, one can look at change in vegetation and soils through time as a test of the tacit assumption that the linear record of vegetation along the bay represents a true chronosequence.

Finally, there is a commitment by the U.S. National Park Service to maintain Glacier Bay National Park and Preserve in a relatively natural state and to support research on plant succession. Thus, studies begun now or in the past can be assured of site security into the indefinite future. Because Glacier Bay is part of a biosphere reserve, it is a particularly appropriate place to initiate and continue long-term studies of processes such as plant succession.

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Effect of Ecosystem Succession on Soil and Streamwater Chemistry in Glacier Bay

by

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Abstract

A useful tool in the assessment of anthropogenic effects on aquatic and terrestrial ecosystems is biogeochemical cycling and ion budgets with quantification of natural factors affecting their variation. Glacier Bay provides a unique opportunity to quantify many such factors. The park has an array of watersheds in primary succession following deglaciation. The output of chemical species in watershed ecosystems is considerably influenced by ecosystem succession. Ecosystem acidification during primary succession is a major factor in determining early ionic loss, but the process is not well studied. Six post-glacial successional stages, varying 20-175+ years since deglaciation, were studied in gauged watersheds within the park. Surface soil pH declined from 7.2 to 5.65 during the first 20 years before revegetation, but subsurface soil chemical changes were minimal. With *Alnus* establishment, soil pH declined to 4.35; soil cation exchange capacity, organic carbon, exchangeable potassium, and nitrate peaked; exchangeable aluminum showed its sharpest increase and soil pH and base saturation their steepest declines. Most nitrate addition to the soil solution occurred as precipitation passed through the forest litter layer. Nitrate provided about 3% of the chemical balance for base cations in incident precipitation and throughfall beneath *Alnus*, all of the base cation concentration in solution passing beneath the litter layer, and 90% in mineral soil solution. The *Populus*-late *Alnus* successional stage exhibited a similar trend. Under *Picea* the nitrate/base cation ratio was similar in throughfall, but nitrate accounted for less than 2% of the base cation concentration in soil solution. The excess nitrate in the early successional watershed appears to reach the stream. There was a shift in the relative proportions of various cations in soil solution with a decrease in proportion of divalents relative to monovalents with increasing soil solution hydrogen concentration. This shift was also reflected in watershed stream chemistry. Such natural changes in ecosystem chemistry must be documented before the more subtle but insidious effects associated with future anthropogenic influences, as contaminated atmospheric deposition, can be assessed.

KEY WORDS: Primary succession, water chemistry, soil chemistry, nitrate, pH, watershed, Glacier Bay.

The input and output balance of chemical species in watershed ecosystems is strongly related to ecosystem succession (Vitousek and Reiners 1975; Gorham et al. 1979). These authors hypothesized that during primary terrestrial succession, chemical element output is initially relatively high. Outputs should decline during the period of high ecosystem productivity and biomass accumulation and then rise again during late successional stages to approximate inputs from precipitation, weathering, and aerosol capture (Gorham et al. 1979).

Vegetation succession patterns following deglaciation in watersheds of Glacier Bay National Park and Preserve have been studied for some time (Cooper 1931; Crocker and Major 1955; Crocker and Dickson 1957). Within ten years of deglaciation, a variable open pioneer stage commences with fireweed (*Epilobium latifolium* L.), variegated horsetail (*Equisetum variegtatum* Schleich.), Dryas *(Dryas drummondii)* and lupine *(Lupinus nootkatensis),* shortly followed by mosses and perhaps a few shrubs. About 25 years after deglaciation, dense thickets of shrubs, primarily Sitka alder [Alnus sinuata (Regel), Rydb. = *Alnus crispa* (Ait.) Pursh spp. *sinuata* (Regel) Hulten] (Hitchcock and Cronquist 1973; Binkley 1981) with a few willow *(Salix sitchensis* Sans. and *S. alexensis* Colville), are formed (Stottlemyer and Rutkowski 1987). After 30-40 years, cottonwood *(Populus trichocarpa* T. and G.) begins to invade followed shortly by

Fig. 1. Watershed study sites, Glacier Bay National Park and Preserve, Gustavus, Alaska.

an occasional Sitka spruce *(Picea sitchensis* Carr.). By about 100 years, Sitka spruce dominates forest vegetation on some sites (Stottlemyer and Rutkowski 1987). The final successional stage, arrived at generally after 200 years, is dominated by hemlocks *(Tsuga heterophylla* Sarg. and *Tsuga mertensiana* Carr.) (Crocker and Dickson 1957).

Basic variations in soil pH, organic matter, carbon and total N following deglaciation have been described (Crocker and Major 1955; Crocker and Dickson 1957; Ugolini 1968). Other aspects remain unstudied, including ecosystem acidification attributable to nitrification and organic acid production, the subsequent downward movement of cations and perhaps anions (NO_3^-) in the soil profile, and the relationship of such movement to ecosystem ion loss in streamflow. Such information is valuable for better understanding of variations in ecosystem processes and to provide a context to assess possible future anthropogenic inputs of similar chemical species.

The objectives of this research were to (1) determine the rate of change in soil chemistry that occurs immediately following deglaciation, (2) relate soil acidification to presence of organic matter and production of soil NO_3^-, (3) estimate the downward movement of ionic species within the soil profiles with increasing acidification and advancing plant succession, and (4) determine if such ionic movements might be reflected in watershed stream chemistry.

Site Description

The watershed sites considered here, Wolf and South Berg (Fig. 1), ranged in time since deglaciation from 30 to an estimated 165 years (Ugolini 1968). The primary site for this study was the first-order Wolf Creek watershed (2350 ha) that contains the Muir Remnant ice sheet. The lower portion of Wolf Creek is dominated by surficial deposits, mainly glacial outwash and till, underlain by detrital clastic rocks. A portion of the upper watershed is underlain by limestone and dolomite. Because of its recent deglaciation, most of the upper watershed adjacent to and above the Muir Remnant is bare rock and glacial debris. The lower 15% of the watershed away from the stream channel is vegetated predominantly by Sitka alder and Dryas.

In the South Berg Bay watershed (1840 ha), deglaciation began about 1835. Present morphology suggests the stream has meandered considerably during this time. The lower one-third of the watershed is dominated by glacial outwash. Most other soils are gravelly humic Lithic Cryorthods. At lower elevations, cottonwood and Sitka alder dominate vegetation next to the stream. Sitka spruce dominates most of the watershed.

Methods

Studies began in summer 1984 and terminated September 1986. Wolf Creek soil samples were collected in late June 1986 from each of the following locations: in proximity to the Muir Remnant on soil without any visible vegetation; 0.5 km to the south on a site vegetated principally by mosses, an occasional scattered alder, and patches of bare soil; and beneath 10-year-old and 24-year-old stands of alder. All sites had northern aspects on the south side of Wolf Creek and were of known age since deglaciation without signs of past or recent alluvial terracing.

To extend the record beyond the maximum aged vegetation on the higher terraces (about 30 years) in Wolf Creek, additional locations were sampled in the South Berg watershed. Samples were collected under 50-year-old cottonwood with a few decadent, old alder trees adjacent the riparian zone and in 90-year-old spruce forest.

Triplicate, 0.6 to 0.9 m deep soil pits, approximately 10 m apart, were dug at each site, and soil horizons, when visible,

identified. Soils without any surface organic layers were sampled in the top 10 cm and at 25 and 40 cm depths (no discernable horizons). Under alder and cottonwood, a 0.1 m^2 frame was used to sample the Oi layer, and mineral horizons were sampled at 2-7 cm (A horizon), 20-25, and 40 cm (C horizon). Beneath spruce, Oi and Oe organic layers were well developed, and mineral horizons were sampled at 2-7 cm (A or Oa/Oe), 25, and 40 cm (C horizon). Laboratory analyses of soil samples followed standard procedures and are described elsewhere (Stottlemyer and Rutkowski 1987).

A continuous record of stream stage height was obtained by a pressure transducer and datalogger mounted in stream sections initially identified by Milner (1987). The USDA Forest Service installed and operated these instruments. Stream samples for inorganic ion analyses and total N were collected in 500 mL amber Nalgene bottles. Stream samples for DOC were collected in 250 mL glass bottles with Teflon caps. Precipitation during the snow-free season was measured every two weeks near each stream discharge station using a polyethylene bulk collector fitted with funnel and pre-rinsed ashless qualitative filter.

In 1985, throughfall and soil solution were sampled in South Berg beneath 20-year-old alder, 60-year-old cottonwood with some decadent old alder adjacent the riparian zone and 90-year-old Sitka spruce. Throughfall and soil solution were not collected in the Wolf Creek drainage because of the potential for bear disturbance and the absence of later vegetation succession stages. Throughfall was collected in each stand using 10 randomly located throughfall collectors. Soil solution was sampled every two weeks in triplicate at two depths, just beneath the forest litter layer and at a 35 cm depth in mineral soil. Details on sample analyses are described elsewhere (Stottlemyer and Rutkowski 1987).

Results and Discussion

Soil Chemistry

Surface mineral soil pH and cation exchange capacity (CEC) showed pronounced change in the 10-20 year period following deglaciation and before revegetation (Fig. 2, Table 1). The change was more rapid than observed at a nearby site, Casement Glacier, due likely to different soil buffering capacity as a result of bedrock character (Ugolini 1968). The pH of volume-weighted precipitation was normal (station mean at Wolf Creek was 6.03). The initial decline in soil pH suggests high inputs of H^+ and carbonic acid in precipitation (80-200 cm/year depending upon elevation).

Soil pH and base saturation sharply declined following establishment of continuous 10- to 24-year-old alder stands. Soil CEC and organic carbon showed the most rapid increase

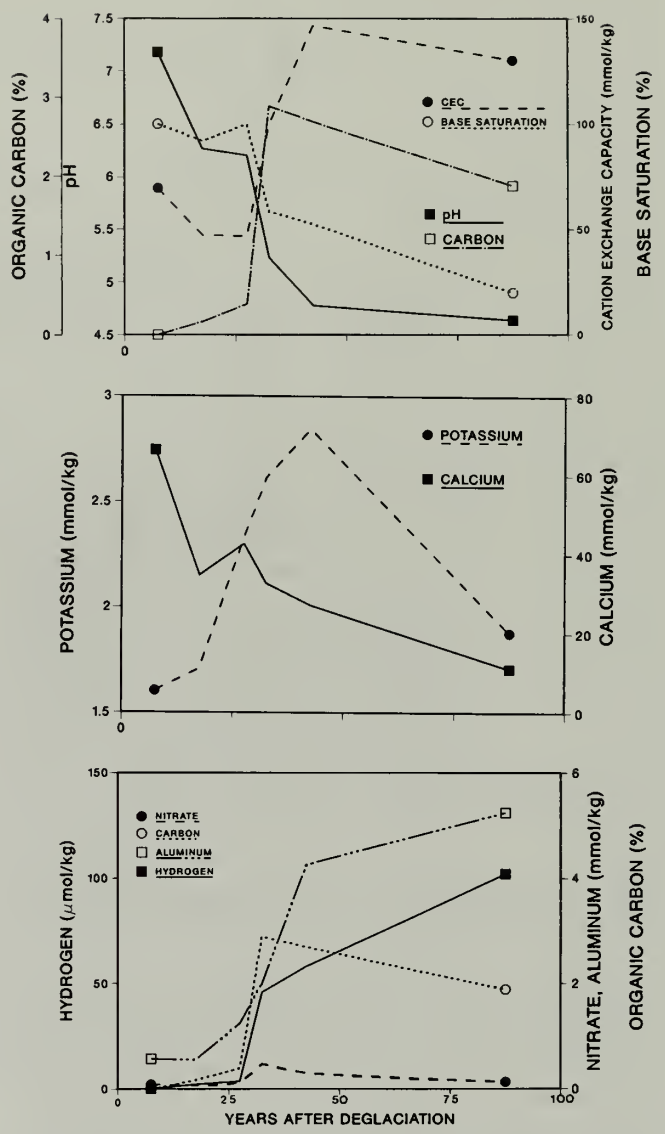

Fig. 2. Mean chemical characteristics of top 15-17 cm of mineral soil following deglaciation and before vegetation cover (0-30 years), beneath 10- and 24-year Alnus at Wolf Creek; and 55-year Populus-Alnus at South Berg.

in later alder successional stages. Within 65 years following deglaciation, surface mineral soil H^+ concentration increased >650x, while its concentration at the deepest sample depth increased 3x. Extractable NO_3^- was highest in surface soil under 24-year-old alder and doubled in concentration at the deepest sample depth. The increase in organic carbon and H^+ increased CEC, reduced pH and base saturation, but did not reduce base cation content. The result was soil acidification with little change in exchangeable base cations.

Until establishment of 24-year-old alder, vegetation effects on subsurface mineral soil horizons appeared minimal (Table 1). During early successional stages, there was a redistribution

Table 1. Physical and chemical characteristics of study plot soils (mean of three samples/plot).

SITE	HORIZON and depth (cm)	GRAVEL CONTENT > 2mm (g/kg)	% C	pH	CEC (mmol/kg)	Base saturation (%)	EXCHANGEABLE CATIONS Ca	Mg	K	Na	Al	NO_3^-
							(mmol/kg)					
Wolf	1 (0-2)	250(57)	0.0	7.17(0.1)	64	100	60.1(14.1)	0.6(0.1)	1.8(0.5)	1.4(0.1)	0.5(0.1)	0.9(0.1)
Remnant	2 (5)	200(30)	0.0	7.19(0.2)	77	100	74.1(7.4)	0.6(0.1)	1.5(0.7)	0.9(0.3)	0.5(0.1)	0.8(0.1)
	3 (10)	592	0.0	7.18(0.1)	71	100	67.9(4.9)	0.6(0.1)	1.4(0.3)	0.7(0.3)	0.7(0.2)	0.8(0.1)
Wolf	C1 (0-2)	63 (53)	0.2(0.0)	5.65(0.3)	15	100	11.7(1.3)	0.4(0.1)	2.0(0.4)	1.7(0.5)	0.7(0.2)	0.8(0.0)
Moss	C2 (15)	91 (123)	0.1(0.1)	6.87(0.1)	79	77	57.7(20.0)	0.4(0.2)	2.0(0.7)	1.3(0.1)	0.4(0.1)	0.8(0.0)
Wolf	A (0-2)	182(166)	0.7(0.2)	5.43(0.3)	19	100	14.5(6.0)	0.8(0.1)	2.9(0.1)	0.8(0.3)	1.6(0.3)	0.2(0.1)
Alder (10 yr)	C2 (15)	150(151)	0.1(0.0)	6.97(0.2)	74	100	70.7(3.0)	0.5(0.1)	1.8(0.4)	1.2(0.3)	0.9(0.2)	0.7(0.0)
Wolf	A (0-2)	526(319)	2.9(0.0)	4.34(0.0)	207	52	90.9(0.0)	8.0(0.0)	5.3(0.0)	2.5(0.0)	1.1(0.0)	0.4(0.0)
Alder	C1 (5)	375(219)	0.7(0.1)	4.73(0.3)	27	51	10.4(5.0)	0.8(0.1)	2.1(0.3)	0.6(0.2)	3.2(0.7)	0.2(0.0)
(24 yr)	C2 (15)	557(106)	0.3(0.1)	6.73(0.1)	56	59	30.6(13.4)	0.6(0.1)	1.2(0.2)	0.7(0.1)	1.2(0.2)	0.1(0.0)
Berg	A (0-2)	2(2)	1.0(0.2)	6.64(0.5)	68	71	41.5(13.0)	4.4(4.0)	1.3(0.2)	0.7(0.5)	1.8(0.2)	0.7(0.3)
Alder	C1 (5)	0(0)	0.2(0.0)	7.03(0.3)	67	78	49.0(1.4)	1.4(0.7)	1.1(0.1)	0.6(0.0)	0.9(0.8)	0.1(0.0)
	C2 (15)	1(1)	0.8(0.2)	7.03(0.2)	59	94	53.2(19.0)	1.4(0.7)	1.1(0.1)	0.4(0.2)	0.8(0.0)	0.4(0.2)
	C2 (30)	649(144)	0.2(0.1)	7.18(0.2)	79	54	40.3(7.4)	0.8(0.2)	0.9(0.3)	0.3(0.2)	0.5(0.1)	0.1(0.0)
Berg	A (0-2)	0(0)	2.2(0.0)	4.24(0.0)	156	17	17.9(0.0)	5.0(0.0)	2.4(0.0)	1.5(0.0)	6.9(0.0)	0.2(0.0)
Poplar	C1 (5)	46(67)	1.2(0.4)	4.37(0.1)	86	15	8.0(1.8)	2.0(0.7)	1.9(0.5)	0.8(0.5)	5.6(0.8)	0.2(0.0)
	C2 (15)	0(0)	0.4(0.0)	5.28(0.0)	11	100	8.7(0.0)	0.7(0.0)	0.8(0.0)	0.3(0.0)	3.2(0.0)	0.0(0.0)
	C2 (30)	0(0)	0.4(0.0)	6.47(0.0)	25	100	23.1(0.0)	0.8(0.0)	1.1(0.0)	0.2(0.0)	1.0(0.0)	0.2(0.0)
Berg	A (0-2)	161(142)	3.2(0.6)	3.99(0.1)	209	9	11.1(0.5)	4.0(0.1)	2.8(0.2)	1.5(0.2)	7.3(1.2)	0.1(0.0)
Spruce	C (15-17)	234(166)	0.5(0.3)	5.27(0.4)	51	28	11.0(1.3)	2.0(1.6)	1.0(0.2)	0.5(0.1)	3.1(1.2)	0.2(0.0)

Table 2. Volume-weighted average annual streamwater chemistry concentrations[1] for South Berg (SB) and Wolf Creeks (WC), Glacier Bay National Park and Preserve, Alaska.

Ion	SB	WC
Ca^{2+}	449(395)	262(172)
Mg^{2+}	56(105)	12(8)
K^+	13(20)	14(7)
Na^+	225(870)	59(33)
NH_4^+	2(5)	2(3)
H^+	.08(.22)	.04(.04)
NO_3^-	4(6)	3(7)
SO_4^{2-}	52(59)	71(44)
Cl^-	182(709)	23(22)
HCO_3^-	868(666)	486(254)
SO_4^{2-}/HCO_3^-	.012	0.29
Total N[2]	0.38(0.20)	0.30(0.16)
Total P	0.03(0.01)	0.03(0.03)
DOC	4.1(3.4)	2.1(1.8)

[1]Concentration in μ mol/L.
[2]Total nitrogen and phosphorus and DOC expressed as mg/L.

of exchangeable Ca^{2+} to deeper soil layers, but no other ion was affected. This trend was reversed in later successional stages. Root penetration was not much below 10 cm. Exchangeable soil NO_3^- below 10 cm depth was probably lost. The increase in soil NO_3^- up through the alder successional stages could account for the observed increase in H^+ concentration. Beyond this successional stage it appears likely that the increase in H^+ concentration was due more to organic acids from the increasing mass of surface organic material. The effects of succession were quite evident on deeper soil chemical and physical properties under cottonwood and very evident in soils beneath Sitka spruce.

The trend in exchangeable base cations reflected bedrock character, soil weathering, changes in CEC with succession, and long-term acidification. At Wolf Creek, exchangeable Ca^{2+} rapidly declined especially in surface mineral soil layers (Table 1) prior to alder establishment. It then increased beneath advanced alder stages due to its still high availability and the increase in CEC with increasing organic matter content. Soil carbon content and CEC peaked at the cottonwood-decadent alder successional stage and then declined. The decline in Ca^{2+} occurred with the decline in CEC, and a fraction of it can be accounted for by increased H^+. Conversely, K^+ concentration increased up to the cottonwood successional stage then began to decline. This ion was strongly conserved regardless of watershed successional status (Table 2), and its decline in soil concentration probably reflects biological uptake or possibly fixation within clay lattices (van Miegroet and Cole 1984).

The increase in total exchangeable aluminum was most rapid between the 24-year-old alder and cottonwood-alder stages. This was concurrent with the most rapid increase in soil H^+ and decrease in exchangeable Ca^{2+} and Mg^{2+}. The effect of longer-term alder presence on exchangable bases can not be assessed from these data. However, it does appear that by later successional stages (Sitka spruce), there has been a major increase in soil H^+ and aluminum with a concurrent reduction in base saturation and Ca^{2+} (Table 1).

Soil Solution Chemistry

The trend in NO_3^- and H^+ ion concentration was very similar in soil solution beneath alder, but NO_3^- concentration far exceeded H^+ concentration. This was the zone where base cations in solution had their most pronounced increase (Fig. 3) suggesting ion exchange or weathering. The high base cation concentrations in soil solution at the C horizon, almost matched by NO_3^- concentration, represent ions which probably were eventually lost from the ecosystem.

Little NO_3^- enters the ecosystem from atmospheric inputs or from throughfall (Fig. 3). It must be assumed that the high soil solution NO_3^- concentration found under alder was generated in the soil. Most NO_3^- addition to the soil solution occurred as precipitation passed through the forest litter layer. In these soils this was probably the zone of maximum microbial activity (Table 1). An increase of strong acid anions, as NO_3^-, in soil solution requires an equivalent increase of cations. Nitrate accounted for about 3% of the chemical ionic balance for base cations in incident precipitation, 5% in throughfall beneath alder, 67% of base cation concentration in solution passing beneath the litter layer, and 88% in mineral soil solution (Fig. 3). The cottonwood-late alder successional stage exhibited a similar trend. Under Sitka spruce the NO_3^-/base cation ratio was similar in throughfall, but NO_3^- accounted for $<1\%$ of the base cation concentration in soil solutions.

There was a shift in the relative proportions of various cations in solution with a decrease in proportion of divalents relative to monovalents with increasing soil solution H^+ concentration. The mean soil solution pH (all depths) was 5.98 under *Alnus*, 4.86 under *Populus—Alnus*, and 4.50 beneath *Picea*. The ratio of divalent to monovalent base cations for the same samples was 5.26, 2.93, and 2.94, respectively. The lowest mean ratio (2.34) for a given depth was beneath the *Picea* litter layer.

A similar trend was evident in soil extractions where the percentage of extractable divalents relative to monovalents

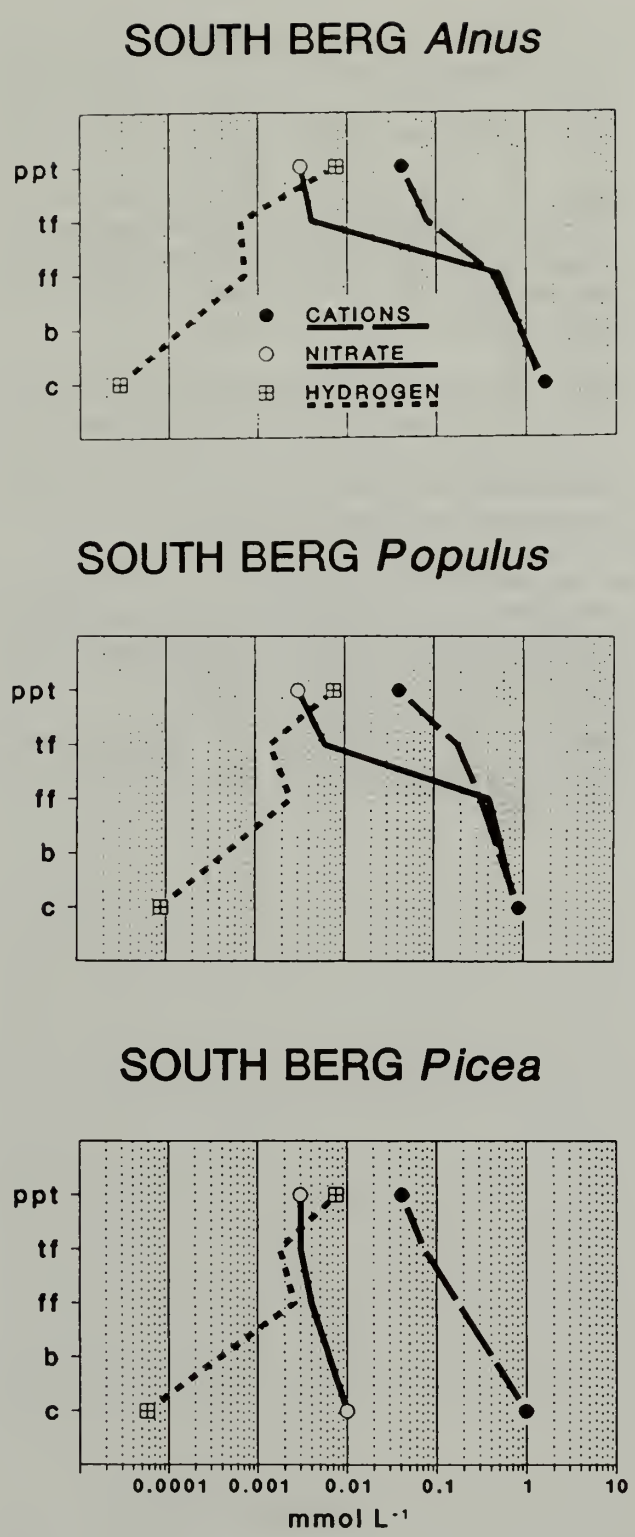

Fig. 3. Volume-weighted precipitation (ppt), volume-weighted throughfall (tf), and tension lysimeter free H^+ (from pH), NO_3^-, and total base cation concentration beneath the forest floor (ff) and at two mineral soil depths (b and c) in successional vegetation at South Berg.

with increasing soil solution H^+ concentration. The mean soil solution pH (all depths) was 5.98 under *Alnus*, 4.86 under *Populus—Alnus*, and 4.50 beneath *Picea*. The ratio of divalent to monovalent base cations for the same samples was 5.26, 2.93, and 2.94, respectively. The lowest mean ratio (2.34) for a given depth was beneath the *Picea* litter layer.

A similar trend was evident in soil extractions where the percentage of extractable divalents relative to monovalents decreased with increasing H^+ (Table 1). Ratios throughout the profiles decline markedly with advancing succession suggesting differences in biological uptake or selective replacement of divalent relative to monovalent bases by H^+ or aluminum.

Stream Chemistry

The effects of this differential base cation leaching at the watershed level are difficult to assess from these limited data. For the two watersheds reported here, the divalent/monovalent ratio (equivalent basis) for streamwater chemistry goes from 7.5 for Wolf Creek to 4.2 for South Berg (Table 2) which is consistent with the hypothesis. However, two watersheds constitute a very limited data set. Discharge from South Berg was also slightly lower in mean pH (7.2) than for Wolf Creek (7.4). But geology maps suggest that there are more carbonate deposits in Wolf Creek. Far more complete assessments of variation in soil quality would be necessary to extrapolate such data to the watershed level.

Volume-weighted stream NO_3^- concentration was almost the same for both watersheds. However, the NO_3^- loss per unit area vegetated was >6x that observed for South Berg. The discharge of total organic compounds per unit area vegetated was also higher in Wolf Creek (total N = 5x, DOC = 3x, Table 2). Although Wolf Creek is a turbid stream (glacial flour), filamentous algal growth is present, and some of this organic production may originate within the stream (Milner 1987).

In sum, the NO_3^- in soil solution beneath early successional stages accounted for a very substantial portion of base cations in solution, but not in streamwater. Streamwater anion concentrations are dominated by HCO_3^- (Table 2). Soil solution concentrations of HCO_3^- in the upper C horizon were near or at zero. Therefore, stream discharge quality would not be expected to describe soil conditions but the influence of subsoil and bedrock conditions.

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Inference and Verification In Chronosequence Studies At Glacier Bay

by

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Abstract

Previous studies of terrestrial plant succession at Glacier Bay National Park have relied on inferences based on observations of a chronosequence of plant communities. Such inference from an unreplicated chronosequence is subject to error unless each study site along the chronosequence has developed along similar successional pathways. Preliminary results of an analysis of the vegetation history at six sites in Glacier Bay National Park suggest that the successional pathway near the terminal moraine at Bartlett Cove differed from the pathway followed at younger sites in Muir Inlet. Differences in the early importance of nitrogen-fixing alder suggest that the distinct pathways could result in ecosystem-level divergence. The presence of multiple successional pathways requires that inference from the Glacier Bay chronosequence be verified by historical reconstructions at single sites, independent replication, or experimental studies.

KEY WORDS: Chronosequence, facilitation, Glacier Bay, multiple pathways, primary succession, vegetation history.

Since William Cooper's first visit to Glacier Bay in 1916, models of plant succession have been substantially influenced by published descriptions of plant communities along the Glacier Bay fjord. Symbiotic nitrogen fixation by colonizing plants and its possible role in facilitation of later plant populations at Glacier Bay are commonly cited in reviews of succession research (e.g., Connell and Slayter 1977; McIntosh 1981; Finegan 1984). Detailed descriptions of the plant communities at Glacier Bay continue to appear in major ecology textbooks as a classic example of primary succession (e.g., Begon et al. 1986; Kimmins 1987). Most of the published information about succession at Glacier Bay is based on inference from observations of a chronosequence of contemporary plant communities between retreating glaciers and the 18th century terminal moraine. The assumptions on which these chronosequence studies rely have not been tested at Glacier Bay.

The Chronosequence Approach

Studies of chronosequences abound in the literature on succession and are the most common source of information about long-term successional patterns. Inference of successional trends from a chronosequence relies on the critical assumption that the spatial sequence of communities from young to old sites is equivalent to the temporal sequence through which the older communities have developed. Measurement of the same community characteristic at each chronosequence stage provides a pattern which is inferred to approximate the actual pattern of change at all stages (Fig. 1a). This approach is warranted only if the differences among communities along the chronosequence are due to age alone and not to other ecologically important variables. If one or more stages along a chronosequence has had a history different from other stages, the successional pattern inferred from the chronosequence may be substantially different from the actual pathway followed at any stage (Fig. 1b). Only the rate of change of a measured characteristic must differ between stages to result in an erroneous inference (Fig. 1c). Thus, for the study of successions which include multiple pathways of development (including different rates), the chronosequence approach can be misleading (Pickett 1989).

If a chronosequence includes multiple pathways, knowledge of their presence is a prerequisite to the interpretation of that chronosequence. However, the chronosequence approach by itself has incomplete power to detect multiple pathways. If sampling in replicate study plots on terrain of equal age reveals high among-plot variability, multiple pathways are suggested. But low among-plot variability at a particular

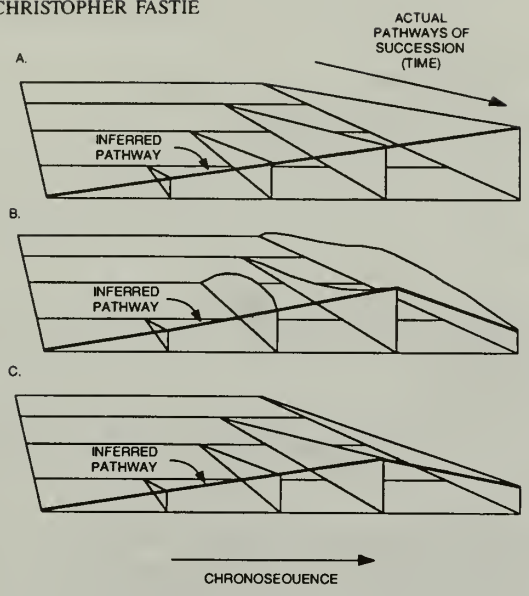

Fig. 1. The relationship between inferred and actual pathways of succession in three hypothetical chronosequences. The actual pathway (change through time) at each chronosequence stage is represented by a vertical surface. (A) Inference from a successional chronosequence is based on the assumption that the actual pathway of succession is the same at all stages along the chronosequence. (B) If successional pathways differ qualitatively among stages, inference from the chronosequence can be misleading. (C) Only the rate of community change need differ among stages in the chronosequence to produce a misleading inference.

terrain age indicates only that a single pathway has been followed at terrain of that age. Older or younger sites could have developed along different pathways in response to local or short-lived environmental extremes. For example, all sites of a particular age could have been affected by an extreme of seed rain, substrate, climate, or disturbance. The chronosequence approach will attribute the unique features of the plant communities at those sites to their age, and not to the actual effects of the environmental extreme. If the environmental extreme is nonrandomly associated with particular stages (e.g., if seed rain varied as a function of distance from the terminal moraine), multiple study sites along the chronosequence cannot be used as independent replicates. Consequently, if inferential statistics are used to demonstrate confidence in the pathway inferred from that chronosequence, the common but serious offense of pseudoreplication (Hurlbert 1984) is committed. Also, directional trends in variance along a decline in within-terrain-age variance with increasing site age does not necessarily indicate successional convergence but could result from the existence of multiple pathways at young sites and a single pathway at all older sites.

Chronosequence studies which are limited to study sites within the Glacier Bay basin may be subject to these errors. Studies of chronosequences associated with other Neoglacial ice retreats in southeastern Alaska could provide the independent replication necessary for interpretation of the Glacier Bay chronosequence. However, the independence of these study sites must also be suspect all 18th century terminal moraines in southeastern Alaska could systematically differ from more recently deglaciated surfaces in (1) proximity to seed sources at the time of deglaciation, (2) texture or hydrology of soil parent material, or (3) local climate at the time of deglaciation.

Verification by the Historical Approach

Chronosequence studies with inadequate replication, including all which rely on a single chronosequence, require verification that the inferred pattern of succession approximates the actual pattern. Natural records of the actual successional patterns at individual sites can provide such verification. Stratigraphic analysis of pollen, micro and macrofossils, and lithology in datable sediments have been used to reconstruct successional patterns on glacial moraines (Birks 1980), in tidal marshes (Clark and Patterson 1985), in dune ponds (Jackson et al. 1988), and in lakes (Engstrom and Fritz, this volume). The annual rings of trees provide tree ages which have been used to infer invasion histories of hemlock-spruce stands in Oregon (Harcombe 1986; Stewart 1986) and of forests in Colorado (Veblen and Lorenz 1986). Tree rings also record annual increment of trunk diameter

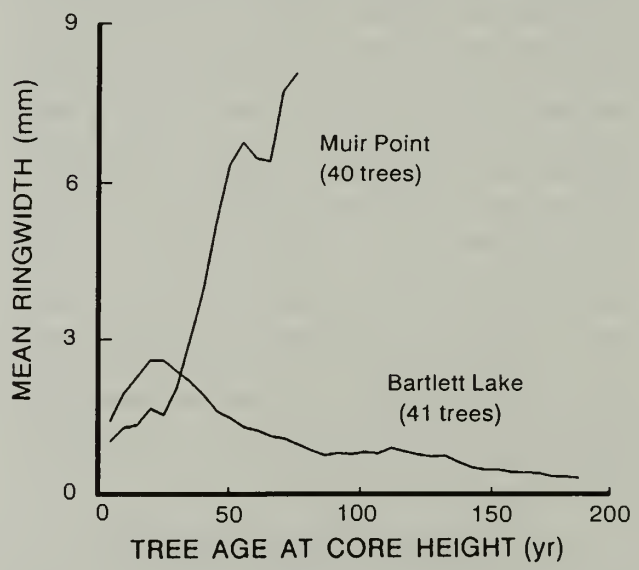

Fig. 2. Five-year means of ringwidth for all dominant Sitka spruce in random sample plots at Muir Point (site age = ca. 215 yr). The trees at Muir Point record a pattern of early suppression and subsequent release which is absent in the record at Bartlett Lake.

and have been used to reconstruct successional patterns of Wyoming forests (Pearson et al. 1987).

A reconstruction of the successional development of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) forests at individual sites at Glacier Bay is underway. Results suggest that the older sites near the mouth of the bay have followed a pathway different from that at younger sites in Muir Inlet, in the upper bay. Tree ages from 400 increment cores were used to reconstruct invasion histories of spruce at six sites along the chronosequence. Preliminary results suggest that after a century of succession in Muir Inlet, the spruce forest is less than half as dense as was the forest near the baymouth after its first century of succession. Comparison of annual radial increments of trunks suggests that spruce near the baymouth established and grew without substantial competition from a shrub thicket, whereas trees in Muir Inlet record dramatic effects of early inhibition (Fig. 2), apparently by a dense thicket of Sitka alder (*Alnus sinuata* [Reg.] Rydb.). Nitrogen-fixing alder continues to be an important component of the centuryold forests in Muir Inlet, but at older sites in the lower part of the bay, closure of the spruce canopy after only 50 to 60 years probably eliminated most understory alder.

Many decades of dominance by nitrogen-fixing alder in Muir Inlet could have caused important and persistent ecosystem-level differences between these young forests and the lowerbay forests where nitrogen-fixation was apparently less important. Consequently, spatial patterns along this chronosequence cannot be used uncritically to infer successional trends. In particular, patterns of accumulation of biomass and nutrients inferred from the chronosequence may not represent the temporal pattern followed at any site. For example, the decline in total soil nitrogen between the 100-year-old and 200-year-old sites described by Crocker and Major (1955) may not represent the change which occurred at the older sites. The inferred decline could be an artifact of a lower rate of soil nitrogen accumulation at the older sites (e.g., Fig. 1C).

The correlation of the inferred decline in total soil nitrogen late in succession with a presumed increase in biomass-nitrogen as spruce trees matured has supported the widely repeated story of facilitation at Glacier Bay—nitrogen fixed by alder is thought to have improved the growth of late successional spruce near the mouth of the bay. The preliminary results from the historical analysis described above suggest that multiple successional pathways make such inference unwarranted.

The Glacier Bay landscape continues to have enormous potential to improve our understanding of succession. The contribution of successional studies based on inference from the Glacier Bay chronosequence will be greatest if their conclusions are verified by historical investigations, by comparisons with similar chronosequences, or by experimental studies.

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Dynamics of Old-growth Temperate Rainforests in Southeast Alaska

by

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Abstract

High annual rainfall and low growing season temperatures make a unique environment for forest development in coastal Alaska. Wind is the dominant form of natural disturbance which maintains species and structural diversity through the creation of canopy gaps. Canopy gaps are colonized primarily by established seedlings of herbaceous and woody plants. Shrubs maximize below-ground growth, and trees maximize height and foliar growth immediately following windthrow. Response of seedlings to disturbance is closely related to percent radiation transmission through the canopy, but overall species composition is often a function of historical factors. Forests arising from catastrophic events are more structurally simple than those arising from repeated partial canopy disturbances. History of disturbance may well be more important than individual tree age in determining the character of old-growth temperate rainforests.

KEY WORDS: Forest ecology, rainforest, forest succession, gap dynamics, wildlife habitat, plant ecology, southeastern Alaska.

Temperate rainforests contrast strikingly with forests of other temperate regions by the wet cool climate under which they grow and in the high-frequency, low-intensity disturbance regimes that perpetuate them (Alaback 1988; Veblen 1989). Abundant year-round moisture and the rarity of lightning storms combine to make wildfire a rare or localized event. Shallow roots, poorly drained soils and high winds, usually during peak rain intensity, combine to make trees highly susceptible to windthrow. Occasionally, a whole swath of forest is leveled by wind storms, especially on steep hillslopes with shallow soils, or on small islands or exposed coastlines. The most pervasive form of wind disturbance, however, is that of single trees or small groups of trees blowing over within a forest.

Recent Forest Service research has been directed toward trying to understand how old-growth rainforests maintain themselves and how natural disturbances influence forest growth and structure. In this study, information from region-wide surveys were combined with intensive studies of a few sites to help better understand the dynamics of low elevation old-growth Sitka spruce-western hemlock (*Picea sitchensis-Tsuga heterophylla*) forests in coastal Alaska. This paper provides an overview of Forest Service research currently underway on this general topic in southeast Alaska.

Methods

Fifteen sites were sampled on flat or gentle topography, at an elevation less than 150 m. All sites were classified as belonging to the more productive western hemlock plant association series, and usually the Alaska blueberry (*Vaccinium alaskaense*) or shield fern associations (*Dryopteris austriaca*) (Martin 1989).

Intensive study plots were established within a site near Juneau, Alaska, on a well-drained podzol (Kupreanof series) derived from micaceous schist with a gentle south to southeast aspect, 30 m in elevation. The forest was composed of old-growth western hemlock and Sitka spruce with dominant trees 150-400 years old. Understory plants were dominated by Alaska blueberry, bunchberry (*Cornus canadensis*), shield fern and the bryophytes *Rhytidiadelphus loreus* and *Hylocomium splendens* (Tappeiner and Alaback 1989).

Ten sampling grids were established within the intensive study area ranging from large gaps (50-m diameter) to dense forest canopy. Percent light interception was measured at 30 points on a grid within two weeks of the summer solstice with 360-degree angle of acceptance quantum (PAR) sensors. Temperature data was collected with temperature transducers interfaced to automated datalogging systems with a resolution of about 0.1 degrees C. Temperature was measured at 10-cm depth for soils, 2-cm depth for litter, and 1.5-4 m for air temperature. In addition, sensors were placed in old tip-up mounds, poorly drained sites, periodically flooded sites, and well-drained sites. Temperatures were measured every 15 seconds and averaged over one-hour intervals.

Plant abundance was estimated with percent canopy cover on 0.1-m^2 microplots centered on each of the light measurement points. Fifty *Tsuga* and *Vaccinium* seedlings were collected to determine biomass allocation and to reconstruct growth, four years after a windthrow event occurred. The seedlings were collected from each of five microsites spanning the range from intact forest edge to the center of the new canopy gap.

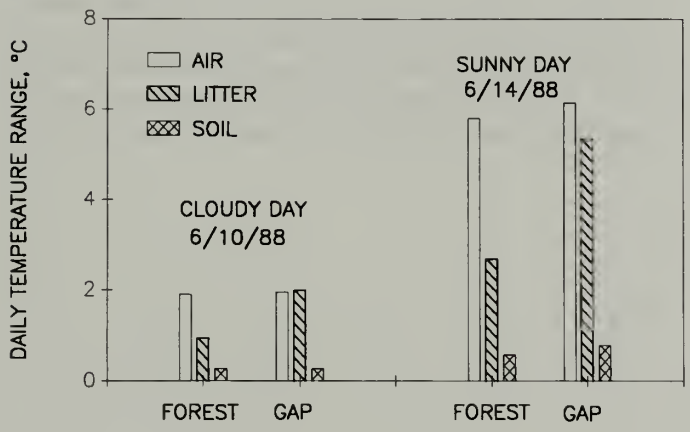

Fig. 1. Changes in microclimate with gap creation. Data represent the daily range in integrated mean hourly temperatures at 2-cm depth (litter), 10-cm depth (soil) and 2 m above the ground (air) in an old-growth colluvial site near Juneau, Alaska.

Results and Discussion

Canopy gaps created by dominant trees falling over created a dramatically different micro-environment than that under continuous canopy cover. Twenty-fold or more of the flux density of diffuse solar radiation reached the forest floor in gaps, usually 10-70% of open sky radiation. Solar energy is particularly limiting to plants in coastal Alaska because of dense overstory canopies, low angle of the sun and high rates of radiation interception by clouds. On clear days, the increased radiation in gaps resulted in elevated litter temperatures of almost 2 degrees C and increased diurnal variation in soil, air and litter temperature (Fig. 1). There was little effect of soils drainage on daily variation in soil temperature (< .5 degree C between windthrow mounds, skunkcabbage (*Lysichiton americanum*), devils club (*Oplopanax horridum*), and well-drained feather moss (*Hylocomium splendens, Rhytidiadelphus loreus*) sites).

Within old-growth, seedlings of herbs and shrubs were rare amongst the dense understory shrubs but were common in gaps or recently windthrown areas. Hemlock seedlings often carpeted mineral and organic surfaces throughout canopy gaps. There were also scattered clusters of Alaska blueberry shrub seedlings which grew as prostrate evergreen sprays. Most tree seedlings were only one year old at the time of the disturbance and were in the cotyledon stage. In less than six months, these seedlings dramatically changed their physiology and metabolism to adapt to the new microclimate, as evidenced by their growth response.

Tree seedlings allocated most biomass to leaves, and generally increased allocation to above-ground growth following windthrow (Fig. 2). Shrubs like blueberry, however, initially increased root and rhizome growth at the expense of foliage. Within 3-4 years, however, shrubs shifted toward increased growth of above-ground components usually coinciding with the production of tall shoots and deciduous leaves. This strategy of building up starch reserves in the root systems so that resprouting potential is established then increasing leaf area for increasing overall growth rate is typical of many woody shrub species and may explain why shrub seedlings take so long to establish in disturbed areas as compared to herb and tree seedlings.

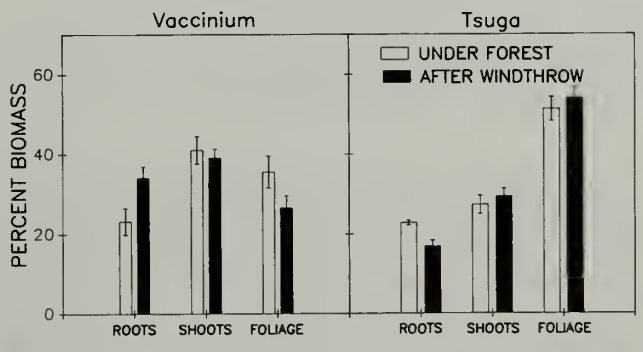

Fig. 2. Biomass allocation for shrub and tree seedlings near the center of the two-year-old canopy gap. Error bars represent 95% confidence limits.

Differences in microclimate within canopy gaps also affected plant seedling growth and structure. The number of branches formed, annual height growth and the proportion of biomass allocated to foliage and roots in tree seedlings changed directly in proportion to the openness of the overstory canopy and the solar radiation that was transmitted through it (Fig. 3). The rate of shrub and herb seedling survival also dramatically increased as a function of radiation intensity. Seed rain appears to increase in gaps, perhaps because of the increased boundary layer roughness and eddy diffusion as winds pass over the upper forest canopy.

The nature and scale of disturbance played a major role in determining the ecosystem response. Small scale disturbance (e.g., 1 or 2 canopy dominants falling) usually resulted in increased vegetative growth first by herbs, then by shrubs, and was shortly followed by overstory tree branches closing the gap again. When larger patches of forest (1-2 tree heights in diameter) were opened up, sufficient time was available for colonization and growth of understory plants so that a complete succession from herbs to shrubs to tree seedlings occurred. When the crowns of individual tree seedlings overlapped, understory shrubs, herbs and even bryophytes were usually shaded out or were buried by litter.

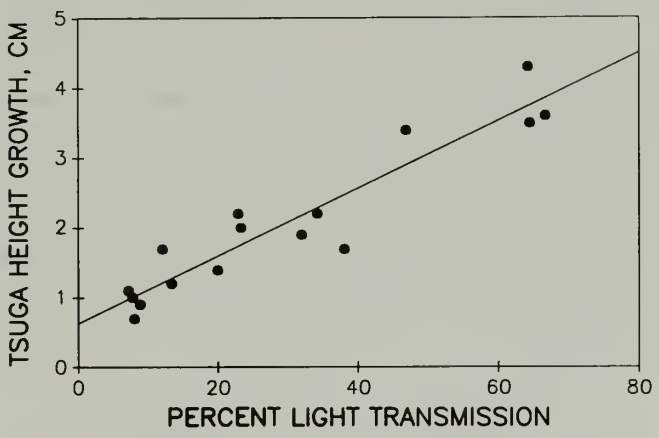

Fig. 3. Tree seedling height growth in relation to available solar radiation within a recent windthrow pocket. Seedlings were measured two years after the disturbance.

Subtle changes in forest canopy structure were often related to the diversity and lushness of the forest. Sidelighting from adjacent canopy openings or natural forest edges were usually associated with increases in species richness. Mixing of forest soils and organic debris by windthrow events may have also contributed to the diversity and fertility of microhabitats on the forest floor (Bowers 1987). Perhaps the richness of the forest was related to how disturbance created spatial and temporal mosaics in which a wide range of plant strategies were of at least temporary advantage.

Catastrophic disturbances do occasionally affect a large area of forest in southeast Alaska (>1 ha). Unless the disturbance stems from glacial retreat, mass wasting, flooding or similar events that initiate primary succession (recolonization of bare ground), the ecosystem response is quite rapid. Following logging, fire or wind, most plant propagules survive the disturbance so they can resprout or begin to grow more rapidly. After approximately 20-30 years, the dense shade of the regenerating forest that follows usually excludes all understory plants for as much as 150 years (Alaback 1982).

As the new rainforest enters its second and third centuries of growth, a few shade-tolerant species of ferns, mosses and tree seedlings recolonize the forest understory. Only after the forest begins to perpetuate itself through the process of gap-dynamics is a true old-growth condition achieved. Old-growth stands typically exhibit a wider variety of reproductive niches for understory plant species and have increased habitat value for wildlife. For there to be a lush diverse understory layer in these northern rainforests, it appears that a dynamic balance between lifeforms and evolutionary strategies needs to develop, usually as a result of repeated generations of tree death and colonization under at least a partially intact mature forest canopy. Thus, the individual age of dominant trees may be far less important for predicting the overall structure and composition of the forest than the history of disturbance and stand development, perhaps extending five centuries or more.

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New Perspectives in Park Science

by

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In the beginning the national parks were anthropocentric. Phineas T. Barnum, on his visit to Yosemite in 1870, conveyed the sense of the age with this comment:

> Unsurpassed and unsurpassable. Look around with pleasure and upward with gratitude.*

A century later, the founding anthropocentric purpose still informed the creed of lifetime ranger Lon Garrison—with the added insights of a century:

> Parks are for the understanding of nature and ourselves; they are for the inspiration that comes from lonely commune with nature and the forces that shape our environment; they are for solace for those troubled by the turbulence of modern civilization.*

From this modern turbulence, with its specter of human species run amok, emerged a biocentric reaction: that Nature—particularly in those last untrammeled vestiges of it, the national parks—was intrinsically valuable, independent of conventional measures of human utility. In its most profound statement, this philosophy maintained that plants, animals, and mountains had rights and souls of their own. This was a Deep Ecology version of the pantheism and spiritual union with Nature that once moved us all. It called back to Eden, to the garden before its violation, to the human innocence and integration that preceded the violation.

The founding ideal of the National Park Service can be viewed as a three-part esthetic: The Wonders of Nature, in both its emotive and intellectual beauties; the health and virility gained from wildlands experience, the Rooseveltian perpetuation of the frontier mythos; and the pure esthetics of artistic and literary expression. Somehow, in the crush of the late 20th century, that ideal had become inadequate. The environmental ethic had crept in.

While public thought and perception evolved, the people of the Park Service doggedly pursued the management of their congressionally mandated dilemma: preservation and use . . .without impairment. But they began to see that parks were more than the pleasuring grounds and mythic landscapes of the founders' vision. For the environmental ethic was contagious. They began to view parks as laboratories and models whence that ethic could be broadcast to the larger society. They began to see that parks could not long endure as refuges from troublous times and encroaching despoliation, lacking public conversion to the environmental ethic.

On another front, as early as the late Twenties with the advent of George Wright's influence, the Park Service began to glimpse the need for science-based management if these marvelous areas were to be preserved. But the Depression, Wright's untimely death, wars, then postwar expansion of the Park System and the deluge of visitors to it, and the Park Service's response to that deluge, combined to shrivel the enlightened beginning. Then came criticism of the hiatus in park science. Followed by a series of studies beginning with the Leopold and Robbins reports of the early Sixties, all calling for order-of-magnitude expansions of scientific research in the parks, for the sake of their own preservation.

Social studies began to make the tie between environmental conditions and human health—physical, mental, social. An earth mortgaged by the parents faced the children yet to come.

Today the expanding horizons of thought have met each other coming around. Now the ecosystem affecting and affected by human beings is clearly seen to be the entire biosphere.

And still, here is the Park Service preserving the natural and cultural environments of the past. In the long view of history, what can be attributed only to an accident of cultural altruism—this setting aside of parklands for the benefit of the people—has become a pragmatic treasure of the utmost current significance. The adventure in cultural edification first embodied in the early parks has held in trust relatively unaltered ecosystems or parts thereof in which, belatedly, we can attempt to discover the workings of this world. . .in which we can measure environmental and cultural changes that threaten the environmental solvency and sanity of the world.

From such studies in the parks can come the communica-

*Both quotations were taken from a manuscript book chapter by S.E. Demars, Professor of Geography, Rhode Island College.

tions—scientific reports, lectures, campfire and school programs, films—that can inform and move the public at large to those reforms of social and individual behaviour that may yet save us, and the parks that give us inspiration.

This traditionalistic institution, which has always fought within itself whether to go along with public demand or to take on the duty of edifying and guiding that demand, has, through its prescient congressional mandate, unwittingly positioned itself and the landscapes it manages for transcendent contribution to this society and the world at large. Its very conservatism, its being a kind of model of cultural lag, finding solace in the past, has fortuitously been its greatest strength. For despite the Service's human foibles, the System stands today relatively intact for the great social purpose of the coming decades. It would seem that social experiments as well as scientific ones can produce unforeseen benefits.

Now opportunity beckons. Through scientific studies using the vast assemblage of natural laboratories preserved by the terms of an earlier vision, the restrictively managed parklands of this Nation—and from that inspiration, of the world—stand ready to synthesize the anthropocentric and biocentric visions so that man can return to the fold as a functioning rather than destructive part of the biosphere. Man in nature, beholden to it for nurture—and reciprocating that care—is no longer an ecofreak.

In this expansion of the meaning and purpose of the National Park System—with its evolving bureaucracy trying to catch up with the evolving world ecosystem—the older mission cannot be lost. Nor, indeed, should we presume to change the words of the Organic Act that in 1916 launched the Service and cohered the System. In its wisdom, the Congress gave us a broad charter, which, like the Constitution, responds elastically to the needs of an evolving society:

> The Service thus established shall promote and regulate the use of the Federal areas known as national parks, national monuments, and reservations. . . by such means and measures as conform to the fundamental purpose of the said parks, monuments, and reservations, which purpose is to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations.

Immanent in this charge is the authority to meet the necessities of a changing world, to marshal the resources and ideas necessary to save the parks, to build upon the founders' philosophy—as a tree grows and extends its branches in its maturity. We must intelligently explicate the evolving mission and purpose and seek congressional sanction for the tools and wherewithal to carry them out. But this added nourishment should flow through the roots that have sustained us all these years. This is no new planting. It is the growth of the original institution.

From the beginning, the parks have been a mosaic of values and functions. These parks, these cultural creations, can and should—through enlightened zoning and land-use dedication—combine traditional public access to beautiful and instructive parklands with scientific utility for social understanding and survival. Environmental standards and aspirations gained from parkland experiences—along with the scientific knowledge derived from parkland study zones—can help guide the larger decisions and reforms that our society must make in the coming decades.

Thus, the founding concept of public use and enjoyment need only be adaptively expanded to accommodate modern socio-scientific imperatives. To the extent that America's parklands contribute to that larger reform, they can save themselves from encroachment and further justify their value to the public. In a world ever more straightened for resources, the park ideal and the parklands themselves will escape exploitative predation only because of their more profound social utility as parklands.

Managing a Biosphere Reserve: Incurred Responsibilities

by

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Abstract

The objectives for establishing biosphere reserves are (1) to conserve genetic diversity by maintaining the structure and functioning of ecosystems, (2) conduct research and monitoring sufficient to understand long-term change in ecosystems and evaluate possible anthropic impacts, and (3) provide for the education and information needs related to these topics. Twenty-five years ago, it was recognized that ecosystems must be studied as single interacting units rather than unconnected components. The design requires long-term, sustained ecological research and monitoring. Its focus is on processes among components, and those factors, both natural and anthropic, affecting transfers of energy and nutrients. The quantification of anthropic impact is complicated by the fact that ecosystem sensitivity is a function of successional status, a major variable at Glacier Bay. But recent research assessing environmental impact suggests that the ecosystem approach is more effective in assessing cumulative impact, the magnitude of impact, and in detecting change earlier. To carry out the complex objectives for biosphere reserves requires an ethical basis for management--generally deficient in U.S. public land managing agencies. Success demands a symbiotic relationship between research institutions and resource managers. This requires that research institutions recognize, emphasize, and support the need for long-term monitoring to provide a context within which ecosystem processes can be studied. It obligates resource managing agencies to provide for longer-term funding and to find new sources of support. It will require researchers to answer questions from land managers, to state the uncertainty that exists, and to document additional research/monitoring needs. It also obligates land managing agencies to professionalize their ranks so that intelligent questions can be asked, and that their managers can respect the opinion of other professionals even when the subject matter or relevance of the proposed action is not fully comprehended.

KEY WORDS: Long-term, ecosystem, Glacier Bay, research, biological diversity, biosphere, MAB, UNESCO.

The International Man and Biosphere (MAB) Program was established in 1970 (UNESCO 1971) at the General Conference of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The overall MAB objectives are (1) to develop the basis within the natural and social sciences for the rational use and conservation of the biosphere and (2) to improve the relationships between man and the biosphere. MAB takes an integrated, interdisciplinary approach focusing on the general study of the structure and function of the biosphere, the systematic observation of change brought about by anthropic stress, the study of the effects of these changes upon human populations, and the educational and information needs related to these subjects. Thus, MAB provides a mechanism for coordinating diverse national and international research, conservation, and training programs. Within MAB there are 14 projects. Seven focus on particular types of geographical areas (islands, mountains, tundra, arid lands, forests, etc.), and six focus on systems and processes such as demographic change, urban systems, etc. Perhaps the project of most interest to the National Park Service, and most directly relevant to Glacier Bay, is Project 8, the International Network of Biosphere Reserves, which established a series of protected areas for research, monitoring, and conservation.

Project 8 came about largely in response to the international concern over the loss of biological diversity (gene "pools") and our relative lack of understanding as to how their supporting ecosystems function. The project has three principal objectives: (1) establish, through ecosystem classification and survey, an international network of representative

protected ecosystems for the conservation of genetic pools, (2) conduct basic ecosystem research to understand their structure and functioning, and (3) increase public awareness and support for such conservation activities through education (UNESCO 1973).

Research is one of the key characteristics of the biosphere reserve program which distinguishes it from most other conservation programs (Franklin 1985). Further, this research is to make a contribution both to "the theoretical and practical aspects of conservation and natural resources management" (UNESCO 1974). The concept that biosphere reserves serve as sites for research important to resource management and for the possible solution of fundamental societal problems has made the program especially attractive to developing nations.

The concept of paired reserves within major biological zones was developed early in the history of the biosphere reserve program in the United States (Franklin 1977). This concept recognized that it was seldom possible to identify a single area that would meet all the needs for a biosphere reserve that is a large intact area with a significant history of research and monitoring and the potential for manipulative research. Many of the most noteworthy conservation areas within the United States are wilderness and park areas which have both limited research histories and potential for manipulative research. Most experimental long-term ecosystem research has been conducted in the Forest Service experimental forests or in conjunction with the National Science Foundation (NSF) Long-term Ecological Research (LTER) program. Thus, almost from its inception, the biosphere reserve program focused on a broad-based research approach ideally incorporating a cluster of sites within each major biotic region.

From its inception the biosphere reserve program recognized that the conservation of genetic diversity was mainly dependent upon maintaining the integrity of a diverse array of ecosystems. To maintain an ecosystem requires an understanding of its structure and functioning. To accomplish this will require in most instances a commitment to long-term, ecosystem-level monitoring (LTEM) and research.

Threats to Park Biosphere Reserves in the United States

In the United States, and I suspect many other countries, there is increasing concern within the professional research communities, and especially among ecologists, over the innate integrity of ecological reserves. This does not appear based on any particular issue or change in national feeling as much as a suspicion that resource management decisions arrived at by public agencies are being made in the absence of a scientific context. While it is customary for public land administrators to generally state that units, such as national parks, are in "good" condition and for opposing groups to proclaim they are "dying," the truth is no one really knows. This concern has been perhaps heightened by a general absence of professional publications or presentations of research and management rationale. One example of this is Yellowstone National Park which identified 46 threats to park resources in the 1980 State of the Parks report to Congress (National Park Service 1980), but in the period 1970-85, as few as nine refereed publications regarding those threats were produced (Lemons 1986).

Global concern over the preservation of national parks and equivalent reserves waxes and wanes often as frequently as does political change and public perception. Clearly, the basis for establishment of policy and management strategy adequate to assure the long-term preservation of natural ecosystems, must be independent of such fluctuation. Unfortunately, most resource conservation/preservation agencies have caused their own entrapment into policies of questionable validity due in large part to databases which are inadequate, both in quality and quantity, to assess ecological change. Compelling factual evidence, not perception, will now be required to correct many of these policies and/or practices.

Twenty-five years ago, it was recognized that ecosystems must be studied as single interacting units rather than unconnected components (Odum 1969). The design requires long-term, sustained ecosystem-level research and monitoring. Within the National Park Service (NPS), the present manner of setting research priorities virtually excludes the possibility of looking at long-term change (Evison 1987). One example is the heavy emphasis placed on resource management plans—documents which for good reason focus principally on the obvious, easily perceived, public-oriented, short-term issues. Within these plans, priorities change rapidly with changes in park personnel. Regional priorities, often derived from a synthesis of park priorities, can be similarly short-termed if not short-sighted. Without doubt these projects warrant attention, but focusing primarily on such issues will never permit the NPS to go on the offensive in mitigating the major threats to national parks. Such mitigation will require formidable peer-reviewed data sets and substantial lead time.

There appears to be a basic reaffirmation by the research community as to the scientific necessity of long-term, systematic environmental monitoring to provide a context within which to formulate and test meaningful hypotheses regarding ecological processes and impacts (Likens 1983, Likens et al. 1986; Schindler 1987, 1988). The need for ecosystem-level research has received additional impetus from

the NSF LTER program and several other national research and monitoring programs. Thus, this may be the ideal time to initiate a new conceptual approach toward research and monitoring in national parks and biosphere reserves.

Need for a New Conceptual Approach in Research

Odum (1963) defined the ecosystem as a biological community plus its non-living environment. It is increasingly evident that the composite assessment of organisms interacting with abiotic components and processes provides the best potential for the early detection of anthropically induced stress and its magnitude (Schindler 1987).

Ecosystem study requires qualitative and quantitative assessment and observation over the long period to develop meaningful and testable hypotheses (Likens 1983). Without knowledge of temporal variation and complexity, it is not likely that meaningful questions can be developed or tested. As we have seen with issues such as atmospheric contaminants, it may take decades for aquatic and terrestrial ecosystems to show significant deviation from natural fluctuation in the variable being measured.

In aquatic ecosystems, there have been few true ecosystem-level studies. Further, there has been little long-term monitoring of aquatic ecosystems except for commercially important species. There are exceptions such as the early long-term research and monitoring efforts of Birge and Juday and Hubbard Brook. But these were clearly the result of dedicated principal investigators—not government or funding agency clairvoyance (Strayer et al. 1986).

In recent years, there has been much emphasis on the use of relatively short-term bioassays of single aquatic species in impact assessments (Schindler 1987). Such efforts tend to be very short-term in nature, and the resultant study conducted primarily to confirm a decision already made. Such studies rarely, if ever, deal with species interaction with the environment, and only by chance lead to furthering of knowledge. Bioassays also do not address species interaction with other biotic or abiotic components and generally focus on species which are convenient to study rather than those which might be the most sensitive to the compound being tested.

To make a current evaluation of the aquatic research and make recommendations on what strategy to pursue in assessing natural and anthropic stress is risky. However, there are a few good long-term studies which tend to indicate that biological components, and especially plankton communities, are the most sensitive indicators of change. The major studies are W. T. Edmondson's classical work in Lake Washington, the Canadian studies in the Experimental Lakes Area of Ontario (Schindler 1987, 1988), the studies of Lake Tahoe (Goldman 1981), and the recent summary from Mirror Lake in New Hampshire (Likens et al. 1986).

The traditional approach to study of the terrestrial ecosystem has also been to intensively examine selected components. These components tend to be biological, especially the large herbivores and carnivores. Unfortunately, large animals are integrators of many factors and therefore generally poor indicators of incipient change in an ecosystem. There may be exceptions. The American alligator in the Everglades, as a sensitive indicator of hydrologic regulation, may be an example (Kushlan 1987).

As with aquatic ecosystems, there have been few ecosystem-level studies of natural or anthropic stress which have included a broad array of organizational and process-oriented study. Therefore, the results of true ecosystem studies cannot yet be compared. While there is free use of the term "ecosystem level" research, most of us are not truly conducting such. In reality, we are either biased or forced for financial reasons toward ecosystem process (function) or component (community) analyses, but not both. Compared to aquatic ecosystems, it appears there are major differences in how terrestrial ecosystems first demonstrate response to stress. At present, it appears that the most sensitive indicators of stress within the terrestrial ecosystem are processes such as primary productivity, decomposition, and nutrient cycling (Bormann 1985, Schindler 1987). Unfortunately, some of these processes, notably primary productivity, are very difficult to measure in terrestrial ecosystems.

Steps must be taken to correct this absence of ecosystem study. For example, everywhere atmospheric inputs have been sampled, airborne contaminants have been found. So the question today is not whether there is air pollution, but what is its effect on ecosystems? Widespread forested regions, particularly in the eastern U.S., may be in the early stages of ecosystem decline (Bormann 1985). It is very difficult to assess the status of terrestrial ecosystems because of their complexity, the poor record of anthropic stress such as change in land use and air pollution, and the natural variation which occurs within their components and processes.

Further, consideration must be given to the energy relationships of such ecosystems and the linkages of the terrestrial ecosystem to interconnected ecosystems and climate. The importance of the terrestrial ecosystems in regulating other biotic systems must not be underestimated. Forested ecosystems regulate the behavior of stream and lake ecosystems (Bormann and Likens 1985) and regional climate (Reifsnyder 1985).

A Strategy for Biosphere Reserves

At present, the NPS considerably underestimates the magnitude and complexity of issues challenging the integrity of the natural resources within the National Park System. It must quickly engage in a formal long-term ecological monitoring and research program with priority placed on the biosphere reserves. To do this requires a formal cooperative effort with the external scientific community, as the NSF and MAB, to supplement its relatively meager internal expertise. This cooperative effort should provide an ad hoc working group of scientists to both help select initial NPS sites for LTEM/LTER and help select and develop projects with park staffs when appropriate. The chief duties of this working group would be (1) site selection, (2) data management among sites, (3) determine what intersite comparisons can or should be strived for, (4) decide on what protocols are to be used in LTEM, (5) locate the horsepower to carry out the tasks, and (6) determine what additional programs are presently collecting data (atmospheric monitoring, surface water, remote sensed, etc.) directly germane to the NPS task.

The major issue is usually site selection which primarily should first consider only a few sites which complement existing LTEM/LTER programs. The difficulty is that one is generally faced with selecting either a site which has greater long-term potential to further scientific knowledge in an ecosystem little studied, as Glacier Bay, with one which may have less long-term scientific potential but which already has a comprehensive ecosystem research and monitoring program underway. Glacier Bay's major scientific value is its diversity of ecosystems in primary succession following deglaciation, the near-absence of human impact on these ecosystems, and the opportunity to study terrestrial-aquatic interactions. The latter is currently a priority in future site selection for the NSF LTER program.

Also, the NPS, with formal involvement of the NSF and MAB, should establish a scientific committee on LTEM/LTER to obtain a better tie with the scientific community and ensure better integration with other LTEM/LTER programs such as those within NSF or the U.S. Forest Service.

Finally, with the cooperation of the NSF, there should be an ad hoc committee established to periodically visit the NPS sites selected for LTEM/LTER. Within three years, the NPS would probably have enough experience, coupled with that gained at the few park sites already engaged in LTEM/LTER, to meaningfully assess the requirements for such a program on a limited number (< 6) of sites. Then it could intelligently explore system expansion and the realities of additional NPS sites, more independently, undertaking meaningful LTEM.

The primary obligation of the land managing agency appears to be providing the stable base funding to maintain an effective core LTEM. As a credible LTEM base accumulates, these sites will become considerably more attractive to both NPS and external scientists in undertaking LTER. This has already proven to be the scenario for some of the NSF LTER network sites and NPS watershed study sites. Funding for LTER is more readily available from a greater number of sources than is funding for LTEM.

Summary and Conclusions

The objectives of the International Biosphere Reserve Program dictate that the responsible agencies implement a long-term inventory/monitoring program to provide a context within which ecosystem-level research may be conducted. Intelligent ecosystem management is a global problem requiring an understanding of ecosystem function and structure. Ecosystem research must focus on component interaction and dynamics rather than just selected components. These obligations were initially incurred by the Park Service when most units, and especially those as Glacier Bay, were entered into the National Park System. While Park Service authority is adequate to address threats originating within park boundaries, most threats to the integrity of park reserves are of external origin (National Park Service 1980). The mitigation of external threats will require a new strategy with an emphasis on providing the substantive basis for needed change. Information truly must be multidisciplinary in nature because to change public policy requires irrefutable evidence that there are no redeeming qualities in the status quo. Often, past commitments, many of which are in legislation, will need rescinding. Most mitigation efforts will affect regional land use patterns—not just point locations. Such efforts will bring on formidable legal challenges to Park Service claims of direct or indirect impact. To meet this opposition requires a virtual institutional change in research and resource management program development and execution. First, a national research strategy needs to be developed for high-priority areas as biosphere reserves. A long-term commitment of stable funding must be made especially for "core" inventory and monitoring.

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How Should Ecologically Threatened Species Be Managed at Glacier Bay?

by

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As human use of Glacier Bay National Park and its surroundings increases, the probability of serious impacts to natural systems is approaching levels that require an active management response. But is active management also required for ecosystem elements that are threatened for "natural" reasons? This question has occurred to me repeatedly in the course of preparing baseline studies at Glacier Bay. Present park management philosophy gives little guidance in constructing an answer.

The overriding goal for management of the Glacier Bay biota has long been agreed upon: it is to be retained in its "natural" condition. That is, it is to be kept essentially free from the influence of technological man. In a place as dynamic as Glacier Bay, this is generally assumed to mean, for instance, that post-glacial successional processes should be allowed to continue essentially unimpeded. Well and good, perhaps, for species whose ecological positions in the park are relatively secure. But it is not so simple in the cases of species which succession or some other natural process is working against.

Let me give an example. The black oystercatcher is a prominent inhabitant of Glacier Bay shores, an unusual circumstance for this species along the inside waters of southern Alaska. Its status at Glacier Bay seems to relate to the abundance of nesting habitat and scarcity of predators in early postglacial landscapes there. However, in recent years, glacial recession has typically ceased or been confined to precipitous terrain, with the result that little shoreline habitat of the sort useful to oystercatchers is being created. At the same time, dense vegetation and predators are encroaching on localities presently used by oystercatchers, making them progressively less suited for use by this species. To compound the problem, increasing human backcountry use is tending to focus on the shoreline habitats most often selected by these birds, and is having a demonstrably negative effect, at least in some instances.

The oystercatcher is not unique in its plight at Glacier Bay. Similar cases can be made with various degrees of success for arctic terns, parasitic jaegers, semipalmated plovers, coyotes, river otters, paper birch and the white-flowered hawkweed, among others.

Species' fortunes are bound to change in terrain with Glacier Bay's dynamism and degree of both topographic and ecological insularity. Yet the appropriate management response is not obvious. On first thought it would seem that, to the degree it is a natural process, drastic reduction or removal of a species from the park biota should be allowed to occur. But three considerations confound this conclusion. First, it is seldom entirely clear what part people have played in a given biotic change. Second, it may not be easy for a species to reestablish itself if and when conditions favor it again (due to insularity, human impacts along the park periphery, etc.). And last, in this world of rapidly shrinking wildlife habitat, reserves of all sorts are viewed as reservoirs of biotic diversity. Do these considerations add up to a rationale for active management to keep an ecologically threatened species in the biota?

It seems to me that in framing an answer to this question in a specific instance, at least two factors must be weighed. To begin with, how much manipulation of the natural situation would have to occur? What if, for instance, vegetational manipulation of a few insular sites was enough to secure the species' presence in the park? Salvaging that species would seem more justifiable, all else being equal, than one for which a great deal of manipulation was necessary.

A second relevant question is the species' regional status. If a species is generally uncommon or in precarious ecological circumstances, the argument for retention would be stronger than for a well-dispersed, abundant resident of south coastal Alaska. The more restricted a species' range, the more compelling this argument becomes.

Early successional habitats and the species they contain are generally the ones presently or potentially under ecological stress at Glacier Bay National Park. This is the case for much of the region's glacier country. A notable exception is at Icy Bay, where major recession has begun within the present

century and continues to bare substantial lowland areas. Thus, Icy Bay should be watched closely by Glacier Bay managers; scarcity or absence in Icy Bay of a species being considered for maintenance management at Glacier Bay is a strong reason to go ahead with the species' protection.

In the long run, the huge Malaspina, Bering and Columbia Glaciers can be expected to recede. Though the precise nature of the terrain they will uncover is difficult to predict, these lands and waters may assume critical importance in long-term retention of early sucessional species in the regional biota.

It follows from the foregoing discussion that farseeing management of the Glacier Bay ecosystem requires a regional outlook, and probably cannot be successful without cooperative management of periglacial areas throughout south coastal Alaska.

Recommendations

Physico-chemical Processes Panel

1. The National Park Service should develop cooperative monitoring efforts with the Canadian and United States geologic services. Monitoring efforts should include seismographic and gravity measurements.

2. We encourage the Park Service to establish meteorological monitoring stations, not only at up-bay sites, but also in the Bartlett Cove area.

3. We encourage the Park Service to support the photopoint work initiated by Dr. William O. Field.

4. We encourage the Park Service to improve overflight coverage of the park to reflect rapid changes in topography, glaciology, and vegetative patterns.

5. We recommend more emphasis on marine systems, especially the oceanography of the fjords. We encourage the Park Service to cooperate with the National Oceanic and Atmospheric Administration to establish tide gauge and current monitoring stations in critical areas to develop an oceanographic model.

6. We recommend that all possible efforts should be made to continue monitoring the work stations established during previous research programs to increase long-term continuity.

7. We recommend the use of remote sensing techniques when possible to decrease impacts to the visitor experience and to wildlife and vegetation.

Panel on Research Related to Resource Management and Human Influence

1. We recommend that research projects draw more from existing studies and literature.

2. We encourage the Park Service to support Tlingit place name and oral history projects.

3. We recommend the documentation and monitoring of social displacement arising from changes in the number and distribution of park visitors.

Ecosystem Development Panel

1. We recommend use of the park as a biological preserve to measure human-influenced and natural patterns of ecosystem change.

2. Investigators should communicate a willingness to assist park management in making key decisions and incorporating research results into interpretive programs for the public. Researchers should submit clearly written reports that are made available in the park library.

3. The Park Service should develop an interdisciplinary project aimed at researching the latter stages of succession in the park by extending existing project work to the Outer Coast. These disciplines should include hydrology, soil chemistry, and development of plant communities.

4. The Park Service should continue stream survey work and salmon escapement counts as part of its ongoing resource monitoring program.

Science and Management Panel

General Strategies

1. We live in an environmentally threatened world. National parks, including Glacier Bay, are not outside the influence of these threats. Parks must serve as laboratories to study and solve long-term, man-induced problems within ecosystems. The anthropocentric and biocentric visions of the Park Service's mission must be synthesized in order to achieve this goal.

2. Land management agencies must develop an ethical basis for managing biosphere reserves. These reserves are too critical on a worldwide basis to be managed in an ethical or moral vacuum.

3. A long-term perspective is required of both manager and researcher in Glacier Bay. Long-term funding must be secured. Closer, symbiotic relationships between the Park Service and research institutions will help.

4. Greg Streveler stated that it was time we, as scientists, "pulled our own weight" in regard to making our work relevant to the present and future needs of Glacier Bay. This includes the formulation of thoughtful and practical research

designs that consider current use patterns and/or management concerns. This strategy demands that results be in a form digestible to managers and scientists alike.

5. Communication is a central key in the incorporation of science and management. Several specific recommendations have been made in this regard, but one general one is that the Park Service should strive to employ professionals who can effectively ask questions of and communicate with researchers.

6. The ultimate role of the manager in Glacier Bay must be to maintain a stable social setting (recreational, scientific, commercial, and subsistence uses) while allowing the biophysical setting to evolve on a natural course.

Specific Recommendations

1. We support the concept of the Science Board which should convene in Glacier Bay for annual conferences. The National Park Service should sponsor these conferences for the primary purpose of distilling solutions to specific park problems. In addition, these conferences would naturally be a time for open communication, direction-setting, and, probably to a lesser degree, proposal review.

2. Before issuing research permits, the Park Service should request the help of the Science Board in reviewing the proposals.

3. The Park Service should continue to refine a program of pre-trip and on-site orientation for researchers. Every scientist who comes to Glacier Bay with a research permit should be oriented personally before heading for the backcountry.

4. Language is the vehicle of communication. The Park Service must encourage scientists to use clear, precise language and minimize jargon in their proposals and final reports. In many cases, a short "lay report" may be needed in addition to the final technical report. The lay report should be requested by the Park Service and made available to managers, interpreters, and the park library.

5. Researchers should be encouraged to give presentations to interpreters and the general public while in Bartlett Cove.

6. The National Park Service must develop an ecosystem approach to management in Glacier Bay. This approach requires the establishment of long-term monitoring and research. Ecosystem research is assumed to include social as well as biophysical elements. The Park Service should not limit itself to a park perspective, but should develop a regional and even a worldwide perspective of systems management in some cases.

7. Ecosystem research must include social elements. Social succession occurs as does biological succession. All human activity, including the scientific, must be monitored and managed carefully if Glacier Bay is to maintain its primitive, natural setting. All human activity in Glacier Bay must be monitored on a long-term basis.

General Recommendations of the Science Panels

1. We recommend that the next symposium be held in the fall of 1993.

2. We suggest the next symposium be named the "Glacier Bay Symposium" and that it should be made more regional in scope (including Yakutat, Hoonah, Elfin Cove, etc.) with expanded emphasis on the arts, ethics, and social sciences.

3. We would like to re-emphasize the recommendations made during the first (1983) symposium which were not fully realized (including transient housing, use of the MV *Nunatak*, etc.). (See Proceedings of the First Glacier Bay Science Symposium, September 23-26, 1983.)

4. We encourage researchers to reoccupy the research sites of former colleagues as an expression of a personal commitment and to alleviate the long-term monitoring versus fundability dilemma.

5. We encourage the park to seek ways to expand its archival facility or use appropriate technology to facilitate access to collection materials.

6. We recommend that the Glacier Bay bibliography be updated from its first printing in 1984.

7. We believe the Glacier Bay Resource Management Plan should include research information as an important resource. The Science Board and research investigators should assist in formulating plans to identify and prioritize critical information needs.

Recommendations of the Glacier Bay Science Board

After a self-analysis evaluation at the Second Glacier Bay Science Symposium on September 18, 1988, a report was read to the meeting on September 19 by the outgoing Board Chairperson, Alexander Milner. The major conclusions were that the Science Board and its functions are still very important with respect to evaluating science in the park and making recommendations for future research. However, to facilitate improved efficiency of the operation of the Science Board, it was agreed that some changes were necessary.

The Science Board will be reduced from seven to three members: one physical scientist, one biological scientist, and one social scientist. In addition, the president of Friends of Glacier Bay or his/her designee and the Superintendent of Glacier Bay National Park and Preserve (GBNPP) are invited to participate as ex-officio, non-voting members. The smaller Board intends to act as an executive group, drawing upon the larger community of scientists for counsel and assistance.

The new Board established at the Symposium consists of Ross Powell (Chairperson), Bill Brown, and Terry Chapin. Ross Powell and Bill Brown will retire after two years, and two new members will be elected. Retiring members from the Board at the Symposium were Alexander Milner (Chairperson), Dave Brew, Dave Duggins, Mark Noble, and Ian Worley.

Other recommendations are as follows:

1. The Science Board chairperson (and other members when possible) should meet annually with the park Superintendent. A good time would be spring when the interpreters receive their orientation. Efforts should also be made to meet at relevant meetings on Alaskan science.

2. Communication between the Science Board and the National Park Service needs to be improved; too often in the past there has been no feedback from the Park Service. The new Science Board chairperson and the new GBNPP Superintendent should explore ways to improve the interaction.

3. We suggest the Park Service employ a resident staff scientist to further improve communication with researchers in the park.

4. All research proposals should be sent to the Science Board for review and comment, including those generated by the Park Service. All proposals should be evaluated for applicability to Glacier Bay National Park and Preserve; those that lack peer review will be reviewed by the Science Board using a list of contributing, qualified scientists in each of the scientific disciplines.

5. Copies of all Investigator's Annual Reports should be sent to the Science Board and all active researchers to provide an overview and to facilitate recommendations for cooperative scientific investigations. These investigator's reports should also be made available for general use by interpreters and managers in Glacier Bay.

6. We wish to re-emphasize the following procedures to encourage individual scientists to discuss their research with the park. Researchers should discuss their plans and problems with the Superintendent or appropriate park scientist. Researchers should give an informal talk to interpreters, naturalists, and park scientists at the start of their summer research season. Park staff should make more of an effort to attend these seminars than they have in the past.

7. We recommend that a 300-word summary of interpretative and management significance of the research should be provided in layman's language as part of a scientific use permit and that this summary should accompany scientific papers sent to the park library.

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